# NAVAL POSTGRADUATE SCHOOL

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# THESIS

**EVALUATION OF LOGISTICS OPERATIONS COMMAND AND CONTROL CAPABILITY: OPTIMIZATION REVISITED**

by

Recep Ozkan

June 2005

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**EVALUATION OF LOGISTICS OPERATIONS COMMAND AND CONTROL CAPABILITY: OPTIMIZATION REVISITED**

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Submitted in partial fulfillment of the
requirements for the degree of

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# ABSTRACT

Logistics Operations Command and Control Capability Concept (LOCCC), developed by Jeff Grelson in 2000, introduces a new distribution principle to combat elements. This concept employs a supporting logistics unit in a general support role and controls it by a unique command center in order to minimize the footprint left by logistics, improve logistic and tactical responsiveness, and reduce the “iron mountain” on the battlefield. This thesis revisits the mathematical models and algorithms developed by Major Thomas Lenhardt to model LOCCC. We preprocess the network topology in order to convert it into an equivalent, simplified network that is computationally tractable with the existing optimization model by using exact and heuristic algorithms. We show that the simplifications and enhancements we propose help us to obtain much faster and better quality solutions than using the original, non-simplified networks. For example, in a ten-minute run, we can obtain a solution that is 98% better in some cases. We also apply the model to a Turkish Infantry Brigade to evaluate LOCCC with sustainment requirements and transportation assets of the Turkish Army.

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## DISCLAIMER

The reader is warned that all the military terminology used in the Turkish Army Manuals and the names of these manuals have been translated by the author for the purpose of this thesis. Therefore, it might not be proper to use them in official documents. All the unit organizations and formations, personnel and equipment quantities, and geographical names in the Turkish Army scenario are notional. They have been assumed and approximated for this study. Real data is kept classified. The computer code used in the thesis cannot be considered validated for use in a different setting than presented in this thesis. Any additional application of the source code or the mathematical model is at the user's own risk.

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# ACKNOWLEDGEMENT

I have met and worked with many brilliant people for the duration of this thesis. I appreciate their warm assistance and dedication. Professor Javier Salmeron, your open door policy, serious and tidy professional principles, inspiration, and patience have been of utmost importance in finishing this thesis. Commander Glenn Lintz, you have reviewed this thesis under tough circumstances in Iraq. Thank you so much for being my second reader. Major Thomas Lenhardt, your help has been beyond my thankfulness. I am grateful for the time and effort you spent for me. I am particularly grateful to Turkish Army for providing me with such a great learning experience.

Finally, I would like to express my gratitude to my wife, Ebru, for her considerateness, altruism, patience and support throughout this study. Her presence has made every difficulty easy to overcome.

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# EXECUTIVE SUMMARY


Logistics Operations Command and Control Capability Concept (LOCCC), developed by Jeff Grelson in 2000, introduces a new distribution principle to combat elements. According to this concept, a Force Service Support Group (FSSG) forms only two Mobile Combat Service Support Detachments (MCSSDs) instead of assigning one to each Regimental Task Force. One of these MCSSDs supports the entire Ground Combat Element in a general support (GS) role while the other adds flexibility to the distribution in a direct support role. Jeff Grelson suggests that LOCCC will: (a) help generate a daily tasking order after receiving supply requests from supported units at a central command and control facility; (b) send the requested support; (c) make necessary modifications to the plan as the tactical situation changes; (d) meet immediate supply requests by taking advantage of having ready GS units as reserve; and (e) reduce the logistics footprint by nearly 60% by lessening the size of the "iron mountain."

Major Thomas Lenhardt studied this concept in 2001 and evaluated the existing and proposed concepts on how to use the Combat Service Support Element resources of a FSSG by solving a vehicle routing problem with demands to be met in specific time windows. This thesis revisits the data structures embedded in Major Lenhardt's mathematical models and algorithms. By making some simplifications and enhancements in these structures, we demonstrate the resulting networks are computationally tractable with the same models, while still maintaining all the necessary information required to devise an optimal distribution schedule.

Specific accomplishments of this thesis are:

- Preprocessing of the network data, which are converted into equivalent data sets that are computationally tractable with the existing model formulation. This is accomplished by applying two essential steps to the original data:
    - Creating a simplified network: Supply has to be delivered to a small number of nodes in the network (the nodes accommodating troops) whereas the majority of nodes serve as transition nodes. These transition

nodes increase the burden of the model in terms of number of variables and equations. We compute all-to-all shortest path distances and then extract transition nodes to simplify the network and reduce the model size. This simplification does not cause any lack of realism in the model, because distances and routes are maintained within our shortest path algorithm. Moreover, rounding the travel times is more accurate in the simplified network (where we round the total travel time between two demand nodes) than in the original network (where we need to round times on each leg).

  - Symmetry breaking: The all-to-all connectivity between the demand nodes causes redundant arcs. The network is simplified further by extracting these replicated arcs, helping the model eliminate redundant solutions.

These enhancements allow us to obtain better solutions in a reasonable time. For example, in one of the cases proposed by Major Lenhardt, the original network would provide a solution consisting of 143.85 stons of unmet demand in 10 minutes. After our enhancements, we attain a solution of 3.14 stons of unmet demand in the same amount of time. The preprocessing time to create the simplified network is, of course, negligible.

- Other managerial and organizational changes in the code, which allow easy access and changes to problem data.
- Application of the model to a Turkish Scenario.
- Allowing reloading (i.e., redelivery) in the model, in order to enhance its realism. This allows us to improve our solution by 2% in some cases of the U.S. Marine Corps scenario and to be able to meet the entire demand in the Turkish Army scenario.
- Trying different vehicle combinations in the heuristic algorithm, in order to assess how the model solution is affected by these modifications.

# I. INTRODUCTION

## A. BACKGROUND

A fighting force is composed of two essential elements: war-fighters and logisticians. The operational success requires their firm solidarity and harmony, because they cannot succeed without each other. History has witnessed many victories and breakdowns linked to the success or failure in acquisition and distribution of logistic supplies, as well as the heroism or cowardice in conducting tactical operations. Napoleon's and Hitler's collapse against Russia in different eras, and the United States´ difficulties to deliver required supplies timely to rapidly advancing forces during Operation Iraqi Freedom are examples of how difficult it can be to execute logistics efficiently. Success stories also exist in different eras. Conquering commanders have always appreciated the role of logistics in combat and have made adequate preparation before embarking on a fight. For example, the Ottoman Empire conducted very long marches to various areas between the 13th and 18th centuries. Local officials had been stocking the necessary supplies and preparing the logistics supply lines on the way to the objective months before the army began moving. Similar groundwork was completed by General Eisenhower before the Normandy landings and by General Schwarzkopf before the Operation Desert Storm. It would be impossible for U.S. troops to succeed in their wars across the ocean without proper logistics. Among multiple applications, logistics planners can employ optimization models to schedule an optimal distribution of supplies to the forces on the battlefield.

### 1. Logistic Distribution in a Marine Air Ground Task Force

A United States Marine Corps (USMC) Marine Air Ground Task Force (MAGTF) Force Service Support Group (FSSG) uses a conventional distribution model, which is roughly a refined version of the one used in the World War II era (Grelson 2000). It consists of a General Support (GS) Combat Service Support Detachment (CSSD) and a Direct Support CSSD that assigns its Mobile Combat Service Support Detachments (MCSSD) to the supported units (Figure 1). That model does not require a real command and control capability. MCSSD assets essentially receive demands from

the units to which they are attached and respond accordingly. MCSSD and supported unit commanders have the initiative to decide the vehicle routing schedules. Unfortunately, when immediately available reserve assets are limited, headquarters lacks the flexibility to take control in case of an urgent demand. Furthermore, transportation assets controlled by subordinate MCSSDs are likely to be inefficient because they consider only meeting the demands of its attached unit. An emerging concept that keeps transportation assets in a general support role is called Logistics Operations Command and Control Capability (LOCCC). LOCCC routes vehicles by a unique command center in CSSD to schedule deliveries making use of the available loading capacity. Centralized control and coordination of the assets also allows the CSSD commander to take immediate actions for suddenly rising demands more easily.

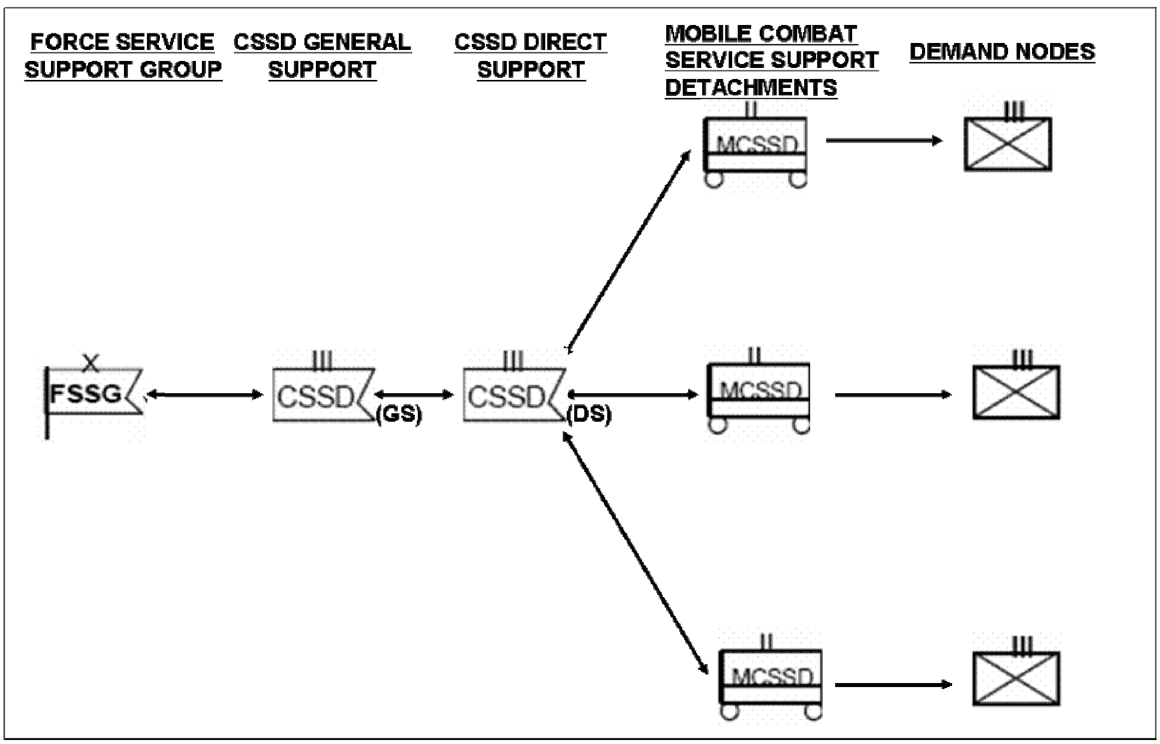


Figure 1. **Distribution model used by a MAGTF FSSG (After Gannon, 2000)**

The United States Marine Corps has ten supply classes. Below are short definitions of supply classes as defined in Marine Corps Warfighting Publication (MCWP) 4-11.

I. Subsistence including rations, health and welfare items.

II. Minor end items.

III. Petroleum, oil, and lubricants (POLs).

IV. Construction materials.

V. Ammunition.

VI. Personal demand items and nonmilitary sales items.

VII. Major end items.

VIII. Medical materiel.

IX. Repair parts.

X. Nonmilitary materiel.

From the above list, water, food, fuel and ammunition expectably occupy most of the loading capacity. Accordingly, this thesis takes into account the first, third and fifth classes of supplies. Other classes are either negligible in terms of demand or require special carrying methods and vehicles; as such, they are not subject to the routing model discussed in this thesis.

Next, we present brief definitions of the service support organizational elements:

***a. Force Service Support Group***

FSSG is the Combat Service Support Element (CSSE) for a Marine Expeditionary Force (MEF). As defined in MCWP 4-11, it is a grouping of functional battalions that provide tactical level ground logistics support to all elements of the MEF.

***b. Combat Service Support Detachment***

CSSDs are special task organizations from various sources tailored to meet logistic needs of the units within the structural body of the MAGTF. Its primary tasks are to rearm, refuel, and provide limited maintenance repair and supply for a supported unit (MCWP 4-24). CSSDs enable the Combat Service Support Commander to provide flexible logistic support to different units. CSSDs can be assigned two different standard missions.

(1) Direct Support: Department of Defense Dictionary of Military and Associated Terms (JP 1-02) defines direct support as “a mission requiring a force to support another specific force and authorizing it to answer directly the supported force’s request for assistance.” Supported and supporting units are in a close one-to-one relationship. A supported unit requests its requirements directly from supporting units.

Higher commanders and headquarters of both sides rarely interfere with the demand and supply process.

(2) General Support: JP 1-02 defines general support as the most centralized mission that is given to the supported force as a whole and not to any particular subdivision thereof. It gives MAGTF and CSSE commanders the opportunity to control the workload and schedule of their subordinates fully and determine the priorities of the demands received from the supported units. The proposed LOCCC concept revolves around GS.

***c. Mobile Combat Service Support Detachment***

MCSSD is the mobile version of a CSSD with the capability to keep pace with a supported maneuver unit. It has the same capabilities as the parent CSSD.

## 2. Logistic Distribution in a Turkish Infantry Brigade

The Turkish Army (TUARM) is executing a transition to a new logistics management system. Most of the subordinate units have already started operating in the new system while the rest are preparing for the transition. The differences between the former system and the new one occur mostly at the strategic level where the automation of demand and response processes enable an effective combination of "pull" and "push" methods. Almost no changes occur regarding the distribution methods of supplies at the brigade level, which is the focus of this thesis.

The push method is active and based on consumption estimates depending on operational tempo. Resources are scheduled to be delivered beforehand according to planning factors. The pull method is more "reactive" than the push method, because it bases the delivery schedule on actual consumption rates of the units on the field rather than on estimates. The supplied units make their requests to the higher commands and pull the supply.

Supply classes are slightly different in TUARM. For example, USMC has ten supply classes, whereas TUARM has six, as specified below (TUARM Field Manual KKT 100-10, 2003):

I. Subsistence and health: Food, fodder (for available animals such as mine dogs, security dogs or mules in mountainous regions), water, cigarettes, sanitary equipment, medicine, etc.

II. Main equipment shown in the formation of the unit and spare parts to replenish this equipment when necessary.

III. Petroleum, oil and lubricant (POL).

IV. Equipment not shown in the formation, but required for special purposes.

V. Ammunition and explosives.

VI. Miscellaneous supplies not included in the first five classes, such as rescued or captured equipment from enemy hands, psychological warfare equipment, maps, water in bulk containers, etc.

Primarily, TUARM uses four distribution methods to deliver supplies (TUARM Field Manual KKT 54-1 1994).

***a. Distribution Methods Used by the Turkish Army***

(1) Take-To-Unit Method: Supplies are delivered to subordinate units by the vehicles provided by superior echelons. Generally, class I supplies are distributed by this method. In today's combat operations, the take-to-unit method is favored and logistics planners are encouraged to seek ways to exploit this method as much as possible. This is because the take-to-unit method allows the higher commanders to have a centralized control over transportation assets. The model discussed in this thesis purely uses this method.

(2) Distribution Node Method: Supplies are received by the subordinate units from superior units' depots. Transportation is executed by the vehicles of the supported units. Generally class II, IV, and V supplies are distributed by this method.

(3) Mixed Method: This method uses a mixture of the first two distribution methods. It is generally used for distribution of class III supplies.

(4) Vehicle-To-Vehicle Method: Supplies are passed from the vehicles of a supporting unit to those of a supported unit at a predetermined meeting

point. This method is the least preferred because of congestion and exposure at the loading zone.

*b. Distribution Methods for I, III and V Supply Classes*

(1) Class I: Food and water have the majority of weight in this supply class. Supply is delivered by the take-to-unit method down to a brigade echelon. Companies and battalions pick up their shares from the distribution node and take them to their kitchens or depots. Since this thesis focuses on brigade level and below, we can accommodate this class of supply in the distribution node method (Figure 2).

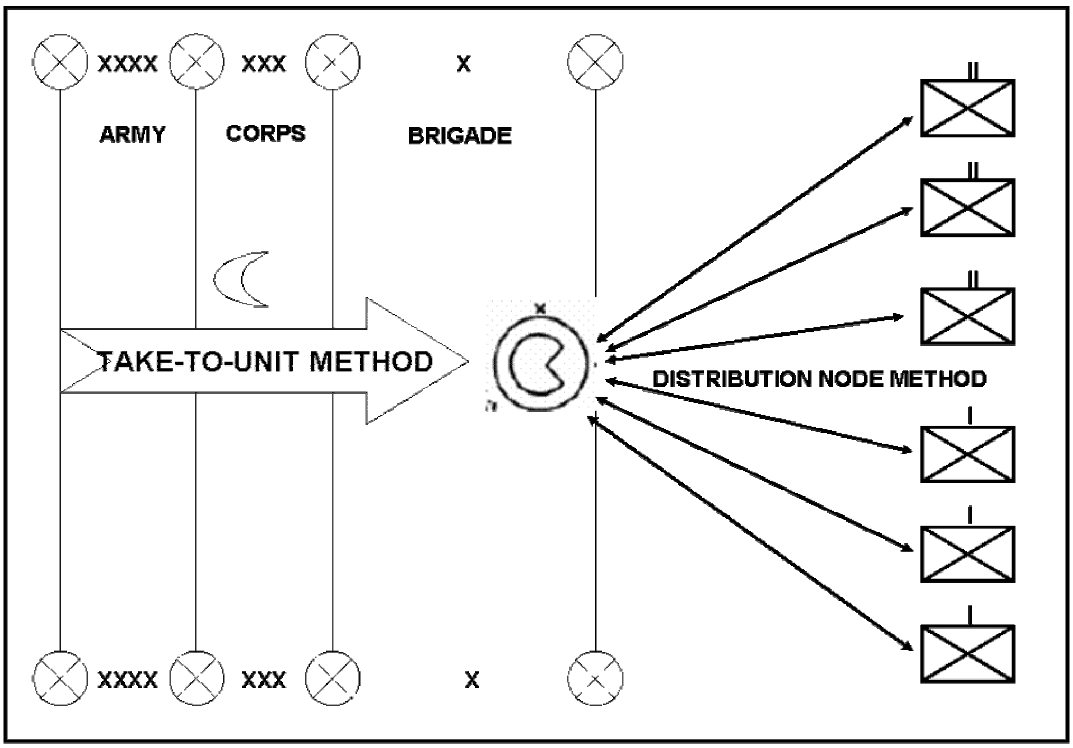


Figure 2. **Distribution of class I supplies at brigade level in TUARM**

(2) Class III: Distribution process of class III is very similar to that of class I. Petroleum Oil and Lubricants (POL) are transported as far forward as possible and supporting units use the take-to-unit method as much as possible. At the brigade level and below, distribution is performed using the distribution node method. Subordinate units collect appropriate empty containers and tankers, refill them at the brigade central distribution node, and deliver them to necessary vehicles (Figure 3).

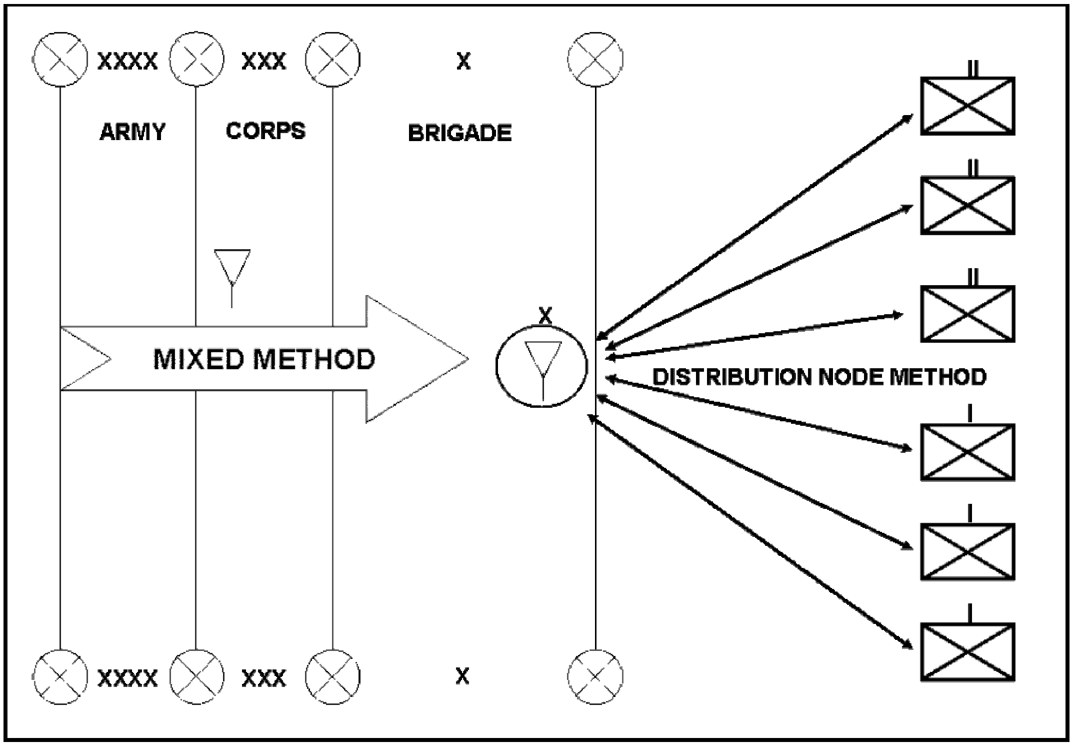


Figure 3. **Distribution of class III supplies at brigade level in TUARM**

(3) Class V: The distribution node method is used to deliver ammunition to the units. The distribution node is located at either army or corps level. A more centralized distribution model takes place for this class of supply (Figure 4).

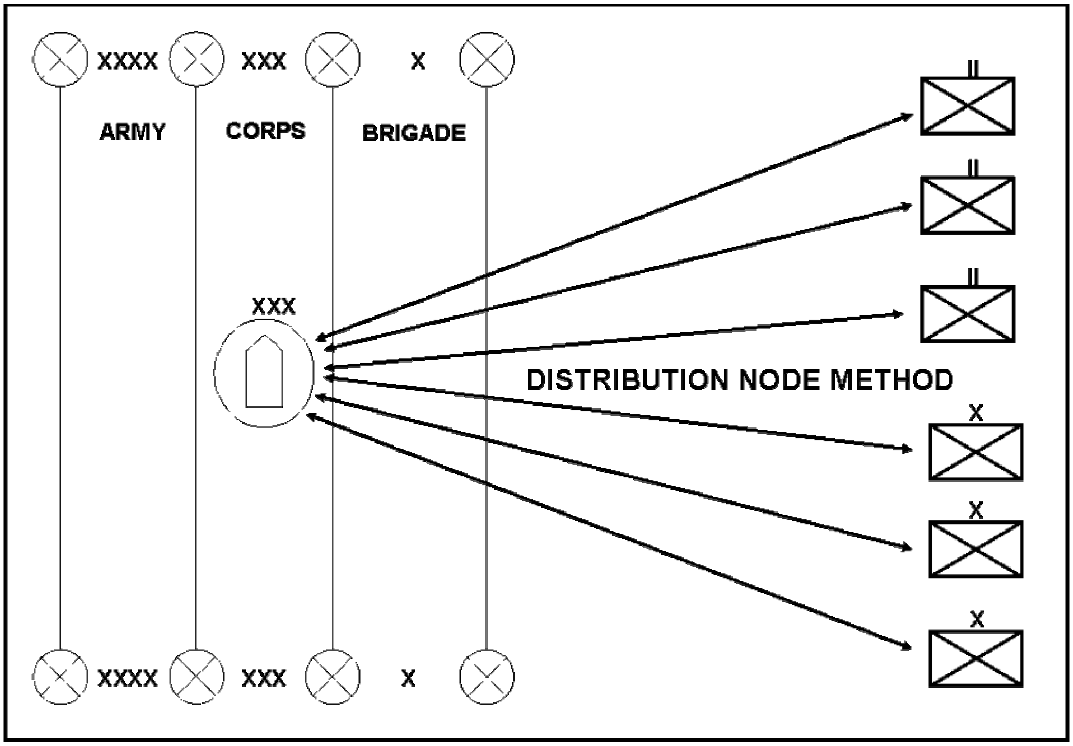


Figure 4. **Distribution of class V supplies at brigade level in TUARM**

In general, TUARM employs the distribution node model for delivery of every class of supply at brigade level and below. Battalions and related companies use their own vehicles to load supplies from the distribution node of the brigade or the corps. Subordinate commanders have the control of the vehicles and they decide which class of supply has the priority to use the transportation assets.

### 3. Logistics Operations Command and Control Capability Concept

The LOCCC concept was proposed by Colonel Jeff Grelson (USMC Ret) (Grelson 2000). Stated logistic goals of MAGTF are to minimize the footprint left by logistics, improve logistic and tactical responsiveness, and reduce the "iron mountain" on the battlefield. Those goals require not only high-technology equipment and weapons, but also efficient and effective command and control capability.

Today's concept of logistics is just a refined version of the one being used in the World War II era (Grelson 2000). CSSE forms one CSSD for the general support missions of the force, and one MCSSD for each maneuver element. Therefore, the

number of logistics units is always one bigger than the number of maneuver units. MCSSDs act as if they were attached to their supported units. Such logistics does not need a sophisticated command and control capability. Command and control is limited to receiving and responding to requests from subordinate units.

In LOCCC, the CSSE will form only two MCSSDs, "one that will provide support to the entire Ground Combat Element in a GS role, and one that will add depth and flexibility to the tactical logistics effort in a direct support role" (Grelson 2000). That direct support MCSSD does a traveling salesman route (Ahuja et al., 1993) from the GS CSSD to the supported task forces (Gannon 2000) (Figure 5). Col Grelson suggests that LOCCC will: (a) help generate a daily tasking order after receiving supply requests from supported units at a central command and control facility; (b) send the requested support; (c) make necessary modifications to the plan as the tactical situation changes; (d) meet immediate supply requests by taking advantage of having ready GS units as reserve; and (e) reduce the logistics footprint by nearly 60% by lessening the size of the "iron mountain." As the size of the iron mountain is reduced, the need for a more effective command and control capability increases, because more effort is required to meet demands with less supply available.

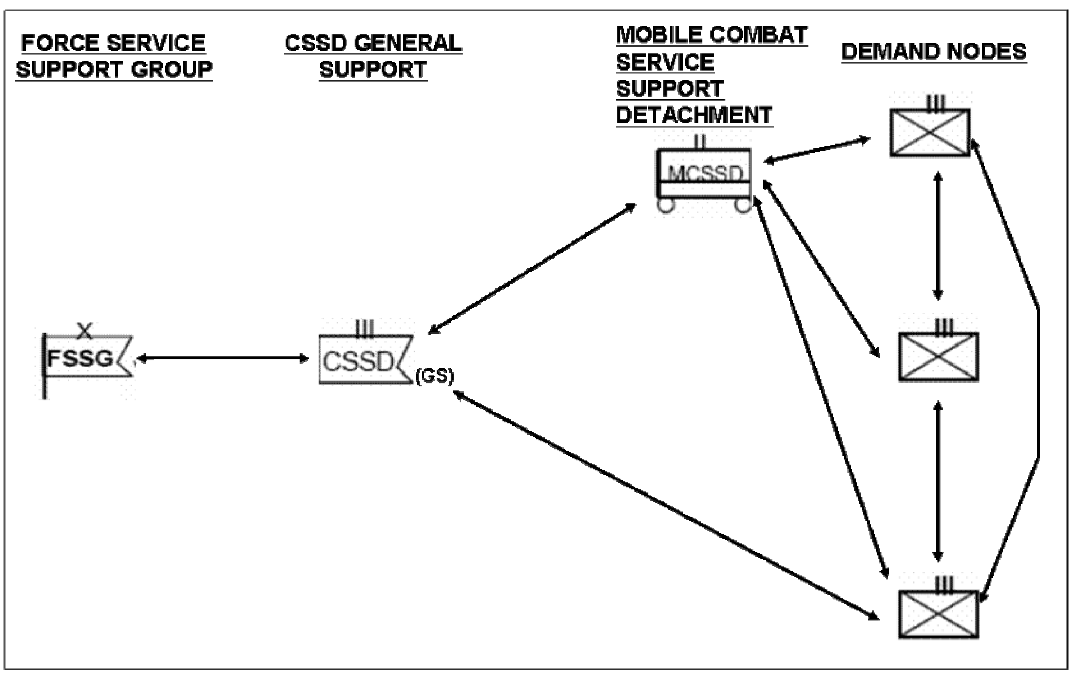


Figure 5. **Distribution model proposed in LOCCC concept**

## B. RECENT STUDIES AND THESIS GOAL

This thesis puts forward an effort to improve the efficiency of the optimization model and methods proposed by Major Lenhardt (Lenhardt 2001) to implement the LOCCC concept.

Unlike many other studies on distribution models, Major Lenhardt did not take airlift logistics capability into account. Theoretically, aircraft are to be assigned to tactical and logistic missions. However, in real life, airlift capability is always exploited by the war fighters to be used in tactical jobs. Major Lenhardt included no airlift or sealift capability in the model, because he realistically considered that the logistics distribution would be assumed by ground transportation assets. His thesis, essentially, evaluated the existing and proposed concepts on how to use the CSSE resources of a FSSG by solving a vehicle routing problem (VRP) with demands to be met in specific time windows. Major Lenhardt coded a discrete event simulation model using the output of an optimization model as the input. He concluded that the vehicular speed was the most significant component to meet the demands in the required time windows. In order to be able to meet the whole demand in the scenario used to evaluate the model, additional ground transportation assets and/or aerial logistic support was required. One of the downsides of the optimization model he implemented was the computational time required to run the full model (i.e., to solve the model exactly, without using heuristics). This thesis enhances Major Lenhardt´s work to make the models and algorithms used computationally more affordable.

A key enhancement is the way we deal with the network data structure. We suggest to convert the given data (e.g., the data originally used by Major Lenhardt) into an equivalent data set that is computationally tractable with the original model formulation. Other managerial and organizational changes in the code allow easy access and changes to problem data.

This thesis also applies the vehicle routing model used for a USMC MAGTF to a Turkish Infantry Brigade. It aims to evaluate the benefits of keeping all the transportation assets of the quartermaster company and the ordnance company gathered and directed by a central command and control facility. From this facility, supplies are delivered to

maneuver units on the field. The total number of vehicles in quartermaster and ordnance companies in a brigade adds up to 75 during wartime. That number is quite larger than 22 vehicles available for a CSSD within the body of MAGTF in USMC (Lenhardt 2001). This thesis will also explore the extent to which the problem with more vehicles can still be solved in affordable time.

We finally incorporate extra features to the model, such as the ability to reload the trucks during the planning time, which is, in fact, a real aspect of the CSSE logistics.

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# II. MODEL FORMULATION

This chapter presents the mathematical formulation of the VRP whose foundation was established by Major Lenhardt (Lenhardt 2001). We discuss: (a) adjustments to allow changes in dispatching order of the vehicles in the heuristic method, (b) adjustments in the data to speed up computations and enhance the accuracy of the results, and (c) adjustments in the model to incorporate multiple loading of the vehicles.

We first define and discuss the VRP specifications, and then describe a mathematical model for this problem.

## A. PROBLEM SPECIFICATIONS

The VRP setting is a distribution network, which comprises nodes (demand sites, or points where two or more roads concur) and roads (hereafter arcs). Arcs are undirected in the network allowing two-way traffic flow, and travel times depend on the arc and vehicle type only (congestion effects, uncertainty due to weather conditions or other contingencies are disregarded).

Nodes have demand only if they accommodate a supported unit. Demand is specified by node, demand type and amount, and a time window when the delivery is supposed to be made (otherwise, the non-delivered fraction of demand is considered unmet). In other words, demand is considered met when one or several vehicles distribute the required cargo within the specified time window. Our goal is, precisely, to minimize total (weighed) unmet demand.

Each available vehicle starts and finishes at the origin node, which represents the CSSE or the loading depot. Meanwhile, it might be en route from one node to another, waiting at a certain node or making delivery.

Different types of vehicles are employed in the VRP. No maintenance needs or attrition are taken into consideration. Vehicles have fuel limitations, which in turn, limit their operating hours and distance per day. All the vehicles in the model maintain a constant speed, which is assumed a datum. Delivery times do not depend on the time of the day that delivery is made, cargo type or the amount the vehicle is carrying, but solely

on vehicle type. Vehicles have maximum capacities for total load and maximum loading capacities for each commodity. Commodities are I, III and V USMC classes of supply, namely meals ready to eat (MRE), water (bottled and bulk), fuel, and ammunition. Certain restrictions apply to transportation of those supply classes. For instance, fuel and ammunition cannot be carried together for security reasons.

## B. MATHEMATICAL FORMULATION

The mathematical model used in this thesis was established by Major Tom A. Lenhardt (Lenhardt 2001). The model is restated here with minor changes.

### 1. Sets and indices

*T*, time periods, $t \in T = \{1, 2, ..., |T|\}$

*C*, commodities, $c \in C$

*V*, vehicles, $v \in V$

*M*, truck types, $m \in M = \{HMMWV, FTON, LVS\}$

*N*, nodes, $i, j \in N$

Note: We assume $0 \in N$ , and node 0 is the origin (CSSE) node.

*A*, set of arcs in the network, $a = (i, j) \in A \subset NxN$

### 2. Parameters (Data)

Note: The unit of measure used for commodities is "short ton" (ston) (2,000 pounds) for the USMC scenario and metric ton (1,000 kilograms) for the TUARM scenario.

$type_{vm,}$ parameter that takes the value 1 if vehicle $v$ is a truck of type $m$ and 0 otherwise.

Note: Each vehicle falls in one and only one type, i.e., $\sum_{m \in M} type_{vm} = 1, \ \forall v \in V$

$dem_{ic,}$ demand of commodity $c$ at node $i$ (stons)

$trav_{ij,}$ travel time between node $i$ and $j$ through arc $a$=($i$,$j$) for $(i, j) \in A$ (number of time periods)

$maxT_v$, maximum route time allowed for vehicle $v$ (number of time periods)

$q_{vc}$, capacity of commodity $c$ in vehicle $v$ (stons)

Note: This parameter is calculated as $q_{vc} = \sum_{m \in M} type_{vm} q^{mc}$, where $q^{mc}$ is a given capacity of commodity $c$ for vehicles of type $m \in M$

$\max q_v$, maximum capacity of vehicle $v$ (stons)

$early_{\mathrm{i}}$, earliest delivery time for node $i$ (time period)

$\mathrm{late}_{\mathrm{i}}$, latest delivery time for node $i$ (time period)

$b_{iv}$, unloading time at node $i$ for vehicle $v$ (number of time periods)

Note: This parameter is calculated as $b_{iv} = \sum_{m \in M} type_{vm} b^{mi}$, where $b^{mi}$ is a given unloading time at node $i$ for vehicles of type $m \in M$

$\beta_{ic}$, penalty per unit for unmet demand of commodity $c$ at node $i$ (penalty unit/short ton)

$bigM$, big scalar used in calculations for loading the Logistics Vehicle System (LVS) and Five Ton (FTON) trucks

Note: We may set $bigM = \sum_{i \in N} \sum_{c \in C} dem_{ic}$.

$\varepsilon$, small value used in the objective function to discourage vehicles from making unnecessary trips. In all examples $\varepsilon$ is chosen as 0.00001, which suffices to accomplish that goal.

### 3. Decision Variables

**Binary Decision Variables**

$X_{vijt}$, 1 if vehicle $v$ starts trip through arc $(i, j) \in A$ in time period t; 0 otherwise

$W_{vit}$, 1 if vehicle $v$ is waiting at $i$ in time period $t$; 0 otherwise

$D_{vit}$, 1 if vehicle $v$ starts delivering cargo at $i$ in time period $t$; 0 otherwise

$LW_v$, 1 if vehicle $v$ acts as a vehicle that transports water

$LF_v$, 1 if vehicle $v$ acts as a vehicle that transports fuel

**Non-negative Decision Variables**

$S_{vict}$, quantity of commodity $c$ served by vehicle $v$ at node i in time period $t$ (stons)

$L_{vc}$, quantity of commodity $c$ loaded in vehicle $v$ (stons)

$U_{ic}$, unmet demand of commodity $c$ at node $i$ (stons)

### 4. Mathematical Formulation of the Vehicle Routing Problem

Minimize

$$\sum_{i \in N} \sum_{c \in C} \beta_{ic} U_{ic} + \sum_{v \in V} \sum_{(i,j) \in A} \sum_{\substack{t \in T| \\ t > late_i}} \varepsilon X_{vijt} + \sum_{i \in N} \sum_{v \in V} \sum_{\substack{t \in T| \\ early_i \le t \le late_i}} \varepsilon D_{vit} \tag{1}$$

Subject to:

$$\sum_{\substack{i \in N| \\ dem_{ic} > 0}} \sum_{\substack{t \in T| \\ early_i \le t \le late_i}} S_{vict} = L_{vc}, \qquad \forall v \in V, c \in C \tag{2}$$

$$S_{vict} \le dem_{ic}\, D_{vit}, \forall v \in V, i \in N, c \in C \mid dem_{ic} > 0\ ,\ early_i \le t \le late_i \tag{3}$$

$$\sum_{\substack{t \in T| \\ early_i \le t \le late_i}} \sum_{v \in V} S_{vict} + U_{ic} = dem_{ic}, \qquad \forall i \in N, c \in C \mid dem_{ic} > 0 \tag{4}$$

$$\sum_{c \in C} L_{vc} \le max\, q_v, \qquad \forall v \in V \tag{5}$$

$$W_{vit} + D_{vi,t-b_{iv}+1} + \sum_{\substack{j \in N | \\ (j,i) \in A}} X_{vji,t-trav_{ji}+1} = W_{vi,t+1} + D_{vi,t+1} + \sum_{\substack{j \in N | \\ (i,j) \in A}} X_{vij,t+1} \ ,$$

$$\forall v \in V, i \in N, t \in T \mid t < |T| \qquad (6)$$

$$LW_v + LF_v \le 1 \ , \qquad \forall v \in V \mid type_{"FTON",v} = 1 \ \text{ or } \ type_{"LVS",v} = 1 \qquad (7)$$

$$L_{v,"water"} + L_{v,"ammo"} \le bigM * LW_v \ ,$$

$$\forall v \in V \mid type_{"FTON",v} = 1 \ \text{ or } \ type_{"LVS",v} = 1 \qquad (8)$$

$$L_{v,"fuel"} \le bigM * LF_v \ ,$$

$$\forall v \in V \mid type_{"FTON",v} = 1 \ \text{ or } \ type_{"LVS",v} = 1 \qquad (9)$$

$$\sum_{\substack{j \in N | \\ (0,j) \in A}} X_{v,0,j,t-\max T_v} \le W_{v,0,t} \ , \qquad \forall v \in V, t \in T \mid t \ge \max T_v \qquad (10)$$

$$\sum_{\substack{i,j \in N | \\ (i,j) \in A}} \sum_{t \in T} trav_{ij} X_{vijt} \le fuel_v \ , \qquad \forall v \in V \qquad (11)$$

$$X_{vijt} + X_{vji,t+trav_{ij}-1} \le 1, \qquad \forall v \in V, \ i,j \in N, t \in T \mid (i,j),(j,i) \in A \ (12)$$

$$W_{v,0,1} = 1, \qquad \forall v \in V \qquad (13)$$

$$W_{v,0,|T|} = 1, \qquad \forall v \in V \qquad (14)$$

$$W_{v,i,1} = 0, \qquad \forall v \in V, i \in N - \{0\} \qquad (15)$$

$$X_{v,i,j,1} = 0, \qquad \forall v \in V, (i,j) \in A \qquad (16)$$

$$D_{vit} = 0, \qquad \forall v \in V, i \in N, t \in T \mid t < early_i \ \text{ or } \ t = 1 \ (17)$$

$$L_{vc} \le q_{vc}, \qquad \forall v \in V, c \in C \qquad (18)$$

$$V_{vijt}, W_{vit}, D_{vit}, LW_v, LF_v \in \{0,1\}, \qquad \forall v \in V, (i,j) \in A, i \in N, t \in T \qquad (19)$$

$$S_{vict}, L_{vc}, U_{ic} \ge 0 \qquad \forall v \in V, i \in N, c \in C, t \in T \qquad (20)$$

## 5. Modifications to the model for the Turkish Army scenario

Equations (7) – (9) are slightly revised for the TUARM scenario. The compatibility constraints apply to all vehicle types in this scenario. The modified equations are as follows:

$$LW_v + LF_v \le 1 \ , \qquad \forall v \in V \qquad \text{(TUARM-7)}$$

$$L_{v,"water"} + L_{v,"ammo"} \leq bigM * LW_v, \qquad \forall v \in V \qquad \text{(TUARM-8)}$$

$$L_{v,"fuel"} \leq bigM * LF_v, \qquad \forall v \in V \qquad \text{(TUARM-9)}$$

## 6. Description of the Formulation

### *a. Objective Function (1)*

We minimize the sum of penalized unmet demand incurred at all nodes. Very small penalties are applied to the vehicles wandering around without delivering anything or making notional deliveries. This would be possible otherwise, because there might be multiple optimal solutions (e.g., in theory, vehicles could move freely once they have served their demand). These penalty values are so small that they do not affect the purpose of the objective function while they discourage the vehicles to take needless actions.

### *b. Loading Constraint (2)*

This constraint prevents the vehicles from delivering more than their loads. It also implies that the total quantity of a particular commodity loaded on all of the vehicles cannot exceed the total demand for that commodity.

### *c. Delivery Constraint (3)*

This constraint prevents the vehicles from delivering more than the node demand for every commodity. It also ensures that the delivery is made in the required time window, but only when the status of the vehicle is suitable for a delivery (i.e., when the vehicle is physically at the incumbent node).

### *d. Demand Constraint (4)*

This constraint keeps track of the met and unmet demand for each commodity at each node.

### *e. Capacity Constraint (5)*

This constraint guarantees that the total load on a vehicle does not exceed its maximum capacity.

### *f. Balance Constraint (6)*

This constraint ensures that a vehicle is at exactly one state at a particular time period. It might be waiting or making delivery at a certain node, or traveling between nodes. Trips between nodes are not interrupted. If a vehicle is directed from

node "*i*" to node "*j*", the completion of that trip is guaranteed. Figure 6 depicts the possible transitions between states at one time step.

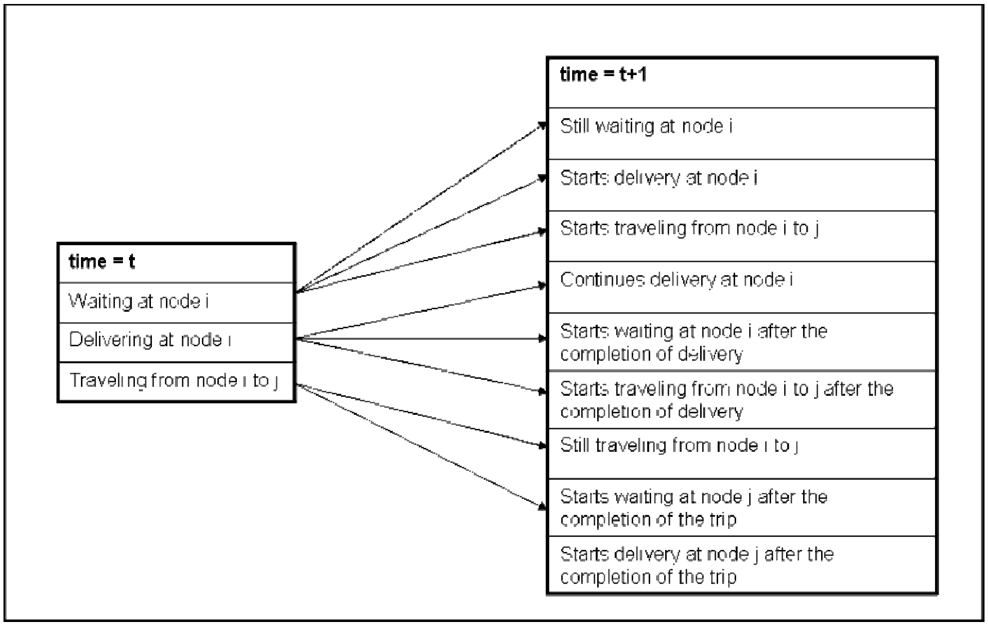


Figure 6. **Description of the vehicle statuses and possible transitions among them**

***g. Compatibility Constraints (7) – (9)***

These constraints arrange the compatibility restrictions concerning the transportation of different types of commodities on the specified vehicle types. Fuel cannot be carried with any other commodity except MRE. Other combinations of commodities are allowed to be carried on the vehicles. For the TUARM scenario we replace (7)-(9) by (TUARM-7)-(TUARM-9).

***h. Driver Shift Constraint (10)***

A driver is not allowed to drive more than ten hours a day in both USMC and Turkish Army scenarios. A driver is forced to be at the origin node before he exceeds his maximum driving time. In this formulation, no driver change is allowed in the model.

***i. Fuel Constraint (11)***

This constraint ensures that vehicles do not operate longer than their capabilities based on fuel capacities. No refueling and/or reloading is allowed (this assumption will be relaxed later in the thesis). Note: Maximum operating hours for all types of vehicles in the USMC scenario were calculated by Major Lenhardt in his thesis

through TM11 240-15/4B. The same calculation is obtained from Turkish Army Regulation KKY 54-5 for the Turkish Army scenario.

***j. Backtracking Constraint (12)***

This constraint aims to help the solver eliminate unrealistic solutions by restricting the vehicles from backtracking on the arcs.

***k. Initial and Final Conditions (13) – (17)***

These constraints ensure all vehicles start and finish at the CSSE node.

***l. Maximum Commodity Capacity (18)***

Each commodity can be loaded on a vehicle up to the vehicle's capacity. This constraint keeps the total quantity of a specific commodity on a vehicle below the maximum capacity applying to that commodity.

***m. Domains for the Decision Variables (19) – ( 20)***

These constraints define the appropriate domains for the binary and non-negative decision variables.

# III. SCENARIO DESCRIPTION

This thesis evaluates two different scenarios. They include the distribution of supplies in a Marine Expeditionary Brigade (MEB) of USMC and in a Mechanized Infantry Brigade of TUARM. The USMC scenario is directly adopted from Major Lenhardt's thesis and no major changes have been made in order to maintain a fair comparison basis after the improvements made in the algorithms, which are described in the next chapter. We also attempt to evaluate LOCCC concept in a Turkish territory, with Turkish soldiers and transportation assets.

## A. U.S. MARINE CORPS SCENARIO AND DATA

Three sub-scenarios are run in this scenario group. Essential differences between these sub-scenarios are the quantities, time windows and locations of demands.

The USMC scenario is taken from an exercise at Marine Corps Air Ground Combat Center in Twenty-nine Palms, California. Notional data from the Operation Steel Knight, the transportation and distribution part of Operation Desert Knight, was used for this exercise.

Sub-scenarios are named as A, B, and C. Scenario A takes account of the full re-supply of a MEB size unit. Scenario B maintains the same unit locations and time windows, but the demands at the nodes are 50% less than the ones in Scenario A in order to represent a partial re-supply of the same unit (Figure 7).

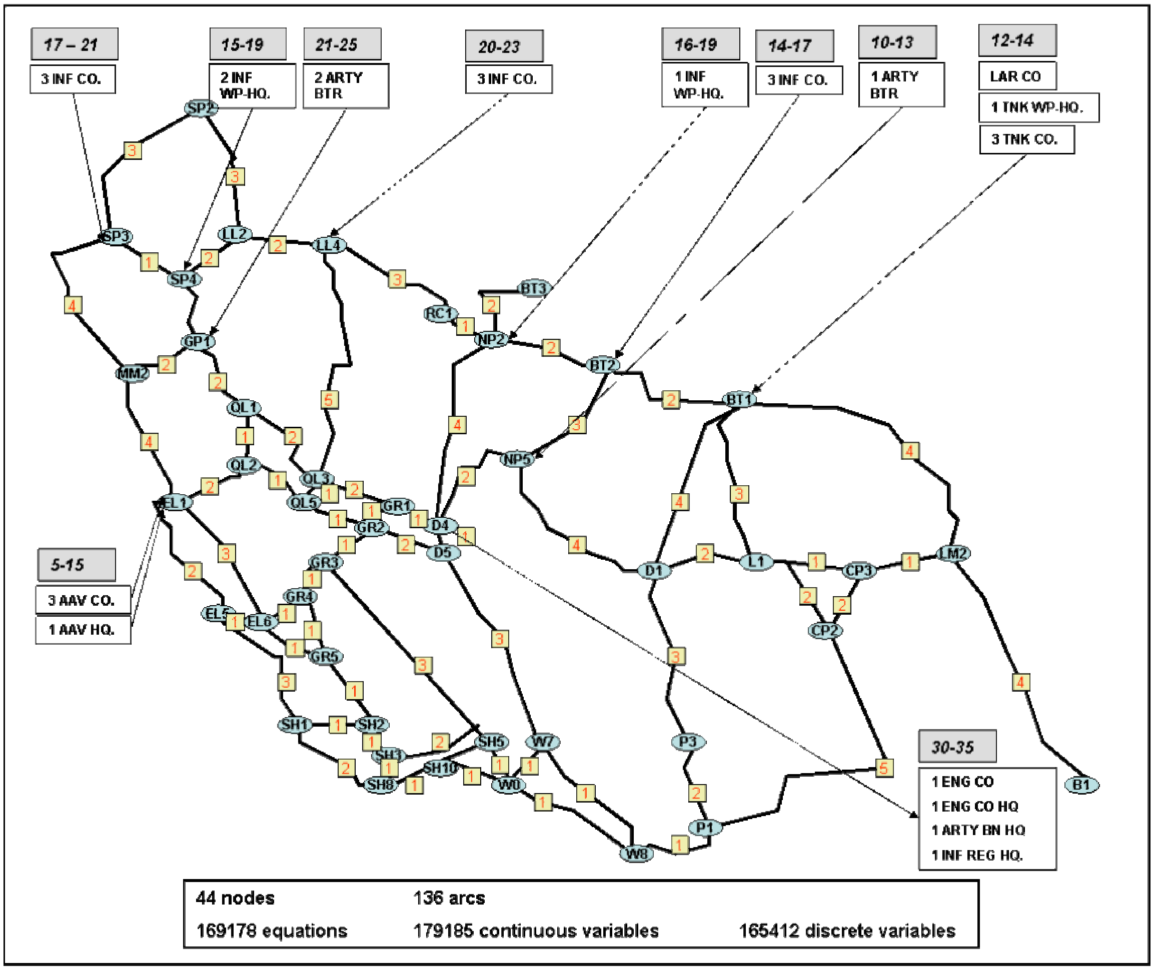


Figure 7. **Graphical representation of the network for scenarios A and B (after Lenhardt, 2001)**

Units are indicated in white boxes. The corresponding delivery time windows to be met are indicated in gray. Oval tags are the abbreviations for the geographical name of the nodes. Square boxes show the time to travel on the associated arc. Time is represented in 20-minute time steps, e.g., the 17-21 time window represents a delivery requirement between 340 and 420 minutes after the beginning of the operation. This network can be used as an overlay to the map of the region, shown in Appendix C.

Scenario C (Figure 8) represents the distribution of supplies to a smaller special task unit. Demands, time windows and the unit locations are completely different from the two previous scenarios.

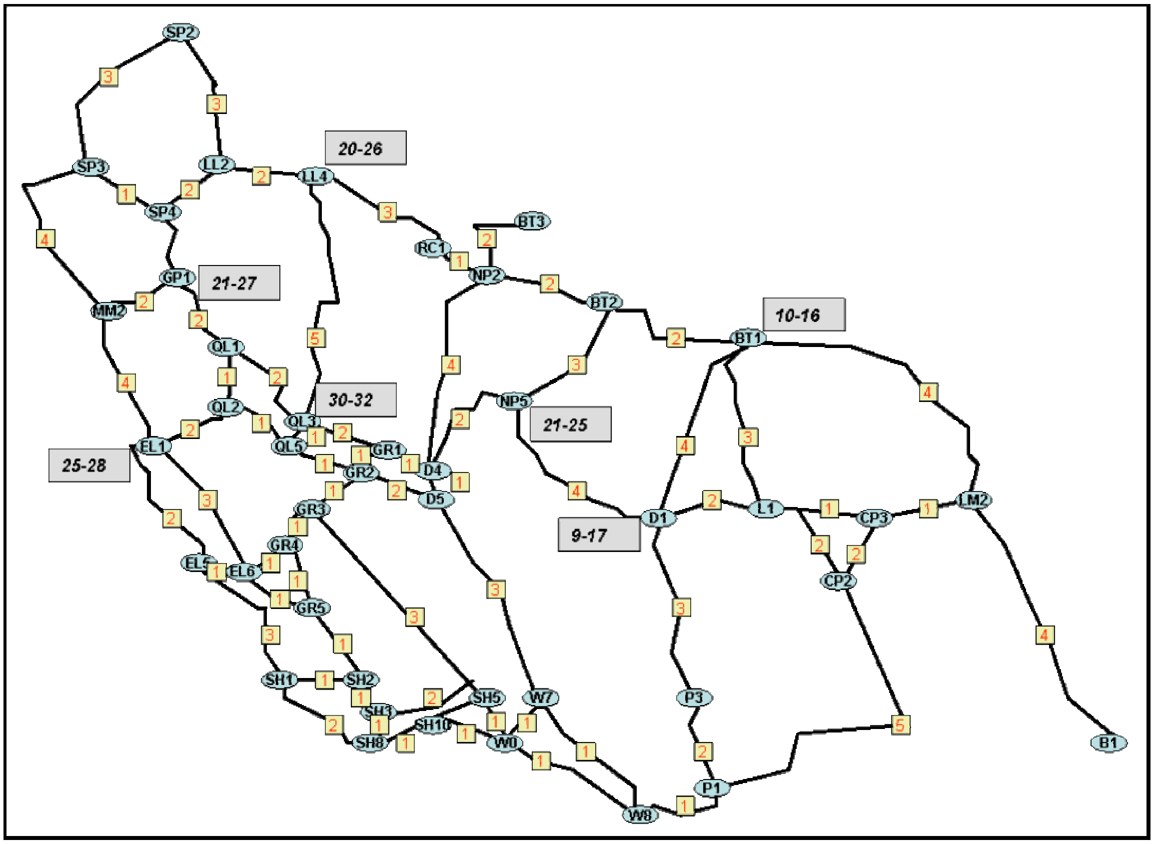


Figure 8. **Graphical representation of the network for scenario C (After Lenhardt, 2001).**

A Special Task Force is employed in this scenario. Unit types are not given in detail in Major Lenhardt's thesis.

Sustainment requirements for the units were computed by using a spreadsheet model called LOG2000 that was developed by Major Neita Armstrong (Armstrong, 2000). These figures are deterministic because they depend solely on planning factors. Only class I, III, and V supplies are included in the model. Appendix C explains computation of sustainment requirements.

Vehicle types and quantities are from Exercise Desert Knight / Desert Steel 2001, Commanding Officer Confirmation Brief (Lenhardt, 2001). There are twenty-two trucks divided into three types (Table 1). Maximum operating time for the vehicles is ten hours. Delivery times are deterministic and originated by Major Lenhardt from Combat Service Support Field Guide. Vehicles are not subject to limitations on driver availability. However, both operating times and fuel capacities are used as constraints in the model.

| TYPE | NUMBER | MAXIMUM CAPACITY (stons) | DELIVERY TIME (min) |
|---|---|---|---|
| 12.5 TON, LVS | 14 | 20.00 | 80 |
| CARGO TRUCK, FTON | 5 | 5.00 | 40 |
| UTILITY TRUCK, HMMWV | 3 | 1.10 | 20 |

Table 1. **Vehicle characteristics in USMC scenario**

Travel times amid the nodes are proportional to the vehicle speed, which is assumed constant and set to 15 km/h. Travel times on arcs are defined in 20-minute time steps and rounded up to the nearest integer number (e.g., all of these three time values: 1.2, 1.7, and 2 would be rounded up to 2 time steps before using them in our model). The unit locations and the time windows in the network are notional as interpreted by Major Lenhardt (2001). Some roads that can never be used in an optimal solution are by-passed or ignored to simplify the model. The distribution process is demonstrated down to the company level. In a real combat operation, platoons and even squads might be located far from each other and separate deliveries to their locations might be needed. Companies or battalions within the proximity of each other are considered as demand zones. A truck is assumed to be at the target even if exact locations of subordinate units might be spread out. Appendix C shows the summaries of demand zones.

## B. TURKISH ARMY SCENARIO AND DATA

This scenario is taken from a preparation course for Turkish War College. It takes place at Trace Region in Northwestern Turkey and incorporates a corps level unit. We have isolated a specific segment that contains the area of responsibility of a mechanized infantry brigade. Some adaptations, such as appropriately positioning the artillery units and defining main supply routes, have been necessary. Time windows are arranged to avoid making the units remain totally off-duty during re-supplying and to make subsequent deliveries to neighboring units (Figure 9). The data are notional because of assumptions and approximations occuring.

Daily sustainment requirements are deterministic and based on planning factors derived from TUARM Directive KKY 54-5. They comprise I, III, and V TUARM class supplies. Appendix C explains daily sustainment requirements.

Vehicle data are all from the war-time records of quartermaster and ordnance companies. Some vehicles might have similar capabilities (even if they are of different types), so they are given generic names in this scenario. The restrictions on maximum operating hours and commodity compatibilities in the USMC scenario apply to this scenario, too. Table 2 shows vehicle characteristics.

| TRUCK TYPE | NUMBER | MAXIMUM CAPACITY (tons) | DELIVERY TIME (min) |
|---|---|---|---|
| LANDROVER | 15 | 1.40 | 20 |
| MERCEDES | 37 | 2.75 | 40 |
| MAN | 5 | 5.00 | 60 |
| TRAILER | 11 | 1.50 | 20 |
| TENTON | 2 | 10.00 | 100 |
| FUELTANKER_SMALL | 3 | 10.00 | 60 |
| FUELTANKER_BIG | 2 | 20.00 | 60 |

Table 2. **Vehicle characteristics in TUARM Scenario**

Travel times are proportional to the speeds of the vehicles. The distribution of supplies is preferred to be conducted at night to take advantage of darkness and relax the traffic on the roads for operational uses during daytime. In the dark and without headlights, trucks are assumed to travel at 16 km/h (KKY 54-5, 1994). Time is represented in 20-minute intervals and each travel time is rounded up to the nearest integer number.

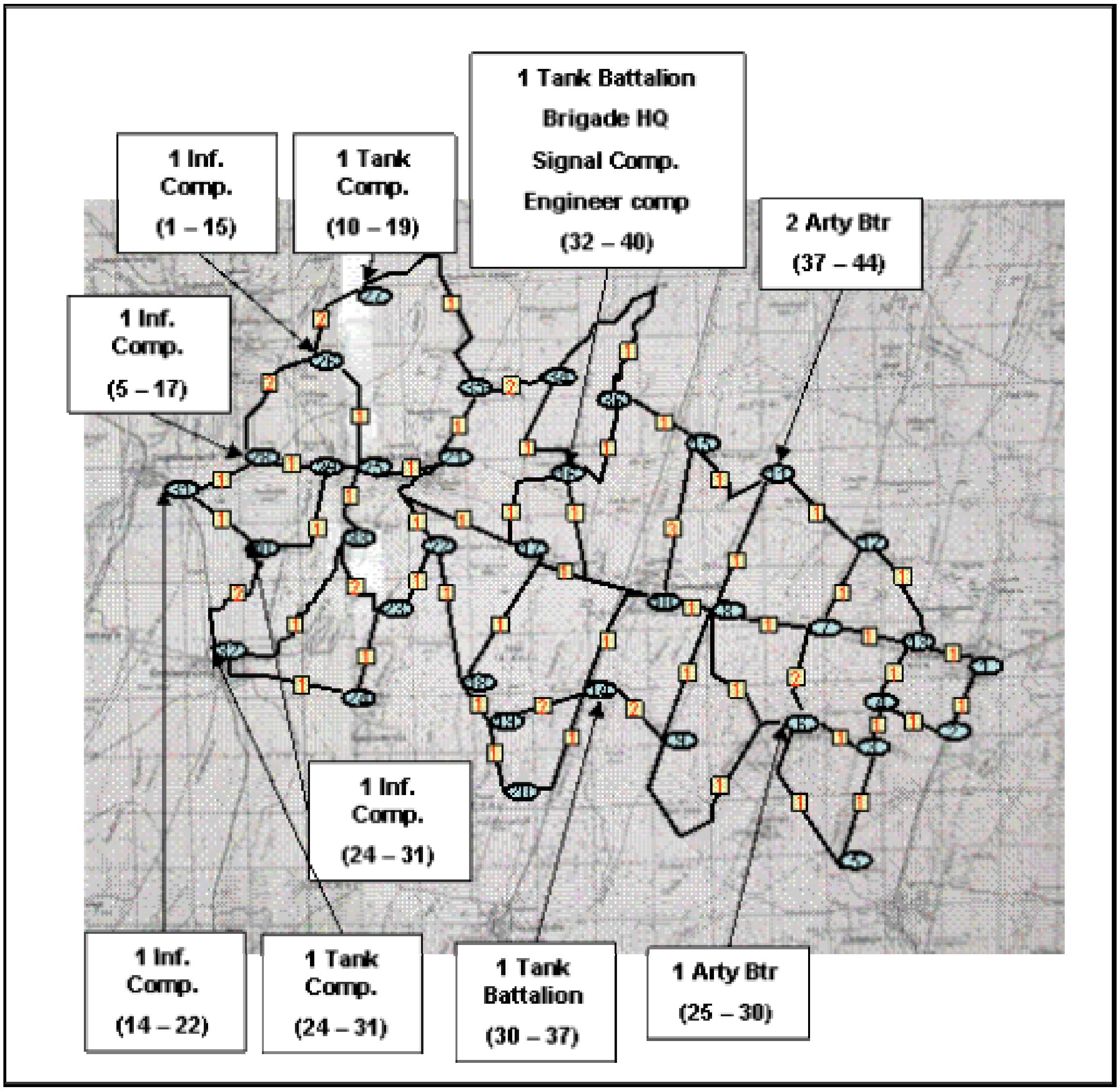


Figure 9. **Graphical representation of the network for TUARM scenario.**

Oval tags represent all nodes in the network. Units located in certain nodes are indicated in white boxes with corresponding delivery time windows in parentheses. Square boxes show the time to travel on the associated arc. Time is represented in 20-minute time steps. This network can be used as an overlay to the map of the region in Appendix C.

# IV. SOLVING THE VEHICLE ROUTING MODEL

## A. HEURISTIC METHOD

The VRP model studied in this thesis is hard to solve exactly, as shown in Lenhardt (2001). For example, each USMC scenario has 169,178 equations, 179,185 continuous variables and 165,412 discrete (binary) variables. Major Lenhardt concluded that reaching a guaranteed optimal solution would require an enormous amount of computational effort. He used a heuristic technique to reach an acceptable (but sub-optimal) solution within affordable time (Table 2).

| scenario | group size | computational time | total unmet demand (stons) | lower bound (stons) | linear relaxation result (stons) |
|---|---|---|---|---|---|
| A | 22 (exact method) | 4h 06m 08s | 61.45 | 27.56 | 7.79 |
| | 2 (heuristic) | 09m 18s | 81.86 | N/A | |
| | 4 (heuristic) | 1h 55m 31s | 73.32 | N/A | |
| B | 22 (exact method) | 4h 05m 18s | 2.87 | 0.00 | 0.00 |
| | 2 (heuristic) | 13m 32s | 0.44 | N/A | |
| | 4 (heuristic) | 41m 25s | 0.97 | N/A | |
| C | 22 (exact method) | 37m 40s | 0.00 | 0.00 | 0.00 |
| | 2 (heuristic) | 24m 17s | 0.00 | N/A | |
| | 4 (heuristic) | 2h 09m 00s | 0.00 | N/A | |

Table 3. **Model results reported in Major Lenhardt's thesis (Lenhardt, 2001)**

Computational times can be affordable only when a heuristic with small vehicle group sizes is used. Heuristics with larger group sizes and the exact method cannot be solved within a reasonable time. Major Lenhardt also devised a lower bound value for the exact method, which helps us to assess how close we are to the optimal solution. In scenario A, the best feasible solution (before the model was interrupted after ten hours, where the best solution was found after approximately four hours) was far from the lower bound. This yielded an absolute optimality gap of 33.89 stons and a relative optimality gap of 55%. For the heuristic, a lower bound can only be obtained by using the linear relaxation of the model. For example, in scenario A, we know a solution under 7.79 stons of unmet demand can never be achieved.

Lenhardt´s heuristic basically separates the vehicles into groups of a pre-determined size and approximates the problem solution by using those groups of vehicles sequentially. The first group of vehicles distributes the supplies myopically (disregarding other vehicles that are available), and turns over the unmet demand to the following

group (Figure 10). The process repeats until all demand is met or all groups are exhausted.

A trade-off exists between using a heuristic to save computational time and achieving an optimal solution. Our heuristic might end up at an optimal or near-optimal solution, without being able to prove it. The simplest way to obtain a lower bound for the heuristic solution is to solve the linear relaxation of the full model (with all vehicles), but in general we expect this bound to be weak. Configurations of the vehicle groups are influential on the heuristic results. We run all the scenarios by using two different configurations of the vehicles: groups of two and groups of four vehicles, respectively.

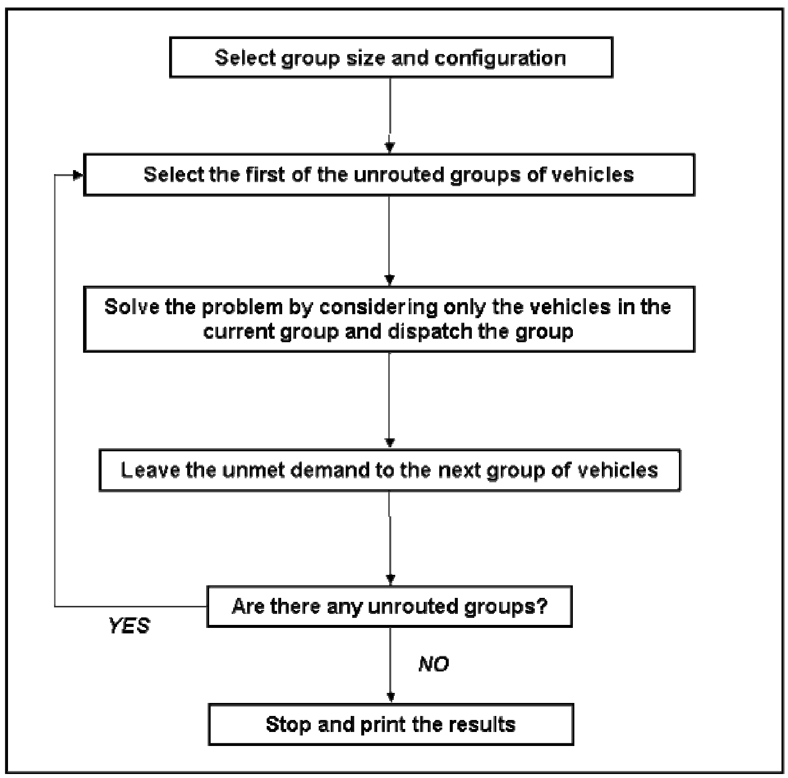


Figure 10. **Heuristic algorithm (after Lenhardt, 2001)**

We need to introduce some notation in order to describe the heuristic algorithm:

$g_v$, group number for vehicle $v$

$g$, order of the group participating in the solution at a heuristic iteration. This scalar is used as a counter, and increases after each heuristic iteration is finished

To formalize the ideas behind the heuristic, let us consider the twenty-two vehicles in the USMC scenario. Assume that a vehicle group contains two trucks. Each vehicle will have a $g_v$ value between 1 and 11 (e.g., $g_v$ = 2 for the third and fourth vehicles, and $g_v$ = 3 for the fifth and sixth). The heuristic algorithm illustrated in Figure 10 can be succinctly stated in the following steps:

(1) Set $G$ (e.g., $G=\{1,2,\ldots 11\}$) and $g_v \in G$, $\forall\, v \in V$.

(2) Set $g$:=1.

(3) Set $V' := \{ v \in V \mid g_v = g\}$.

(4) Solve VRP using $V'$ instead of $V$.

(5) If $g=|G|$, print the solution and STOP.

(6) Update all demands (subtracting the demand met by $v \in V'$); increase $g'$ by 1 and return to step 3.

We also explore modifying the vehicle groups. In his thesis, Major Lenhardt chose to dispatch the vehicles from the first to the last. This grouping choice lets the smallest assets deliver their loads earlier and utilizes the large trucks to meet leftover demands. We investigate whether reversing the grouping order, which allows the larger trucks to deliver the bulk of the demand and allows the smaller ones to accomplish the remaining unmet demand, helps reduce computational time or total unmet demand. The next chapter discusses and compares the results.

## B. ENHANCEMENTS TO SIMPLIFY THE PROBLEM

A decision maker's priority should be obtaining a reasonable (ideally near-optimal) solution within an affordable time. This thesis emphasizes some adjustments and improvements to the existing data model in order to make it computationally treatable.

### 1. Creation of a Simplified Network

Some nodes in the network provide accommodation for military units, so requirements and demands for certain supply classes arise at those nodes. The remaining nodes (with no demand) merely serve for transition purposes. Vehicles either just pass

through or wait at those nodes for some time. Transition nodes constitute the majority of the nodes, thus increasing the burden of the model in terms of the number of variables and equations. We pull those nodes out and simplify the network remarkably by following the next steps:

Step 1: We compute the shortest paths among all nodes. This is done by using a Java (Sun Microsystems, 2005) computer code implementing the Floyd-Warshall algorithm (Ahuja et al., 1993). (See the algorithm in Appendix B.) This algorithm obtains a matrix of shortest path distances and a matrix of predecessor nodes, which enables us to maintain the necessary information about intermediate nodes without keeping them explicitly in our VRP model formulation. For example, assume we have A and D demand nodes, and B and C transition nodes. Suppose the shortest path between A and D is going through B and C. After we remove nodes B and C in the simplified network, the predecessor matrix keeps the travel directions for getting from A to D (see Figures 11 and 12).

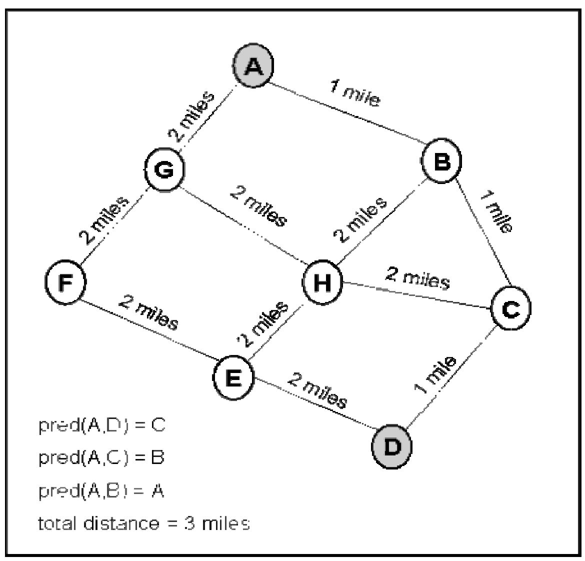


Figure 11. **A sample network before extracting the transition nodes**

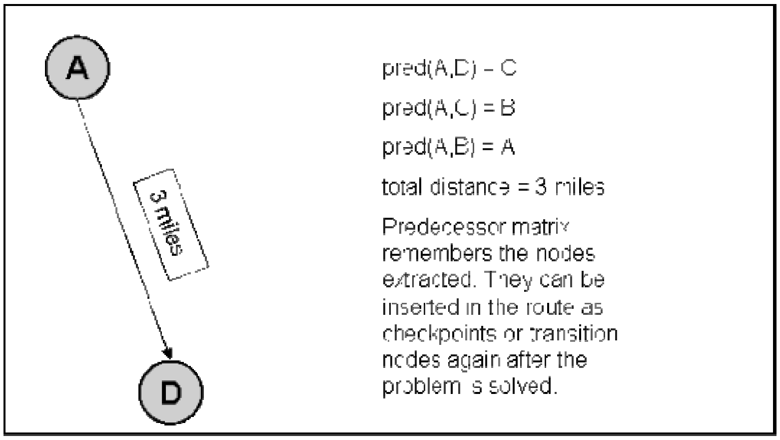


Figure 12. **Simplified network**

The network disregards two intermediate nodes and replaces intermediate arcs by a single arc.

The simplified network has another advantage: Assume in the original network transition times on three adjacent arcs are 1.3, 1.3 and 1.3 time periods, respectively. Each of these is rounded as 2, 2 and 2 (because our time-phased model requires integral travel times), making the total route time equal to 6 time periods (120 minutes), which is clearly an overestimate of the actual route time. If we use the accurate travel times on arcs as the input to the Floyd-Warshall algorithm, total travel time for the route would add up to 3.9 time periods. This would be rounded to the nearest integer, that is, 4 time periods (80 minutes), which is a much better approximation and gives more flexibility to the vehicles to distribute other demands.

Remark: For comparison purposes with Major Lenhardt's results, we still assume the rounded values for each arc that he used (instead of more accurate route travel times).

Finally, since the transition nodes are taken away from the network, vehicles do not have an opportunity to wait at those nodes without making any deliveries. In real life, this feature will facilitate the control and coordination of the vehicles. They will be able to wait only at the origin or the demand nodes.

Step 2: We create the simplified network by eliminating all non-demand nodes and connecting all demand nodes to each other by a directed arc whose length is given by the Floyd – Warshall algorithm.

Consequently, the network in Figure 13 is obtained for scenarios A and B and can be compared to the one in Figure 7.

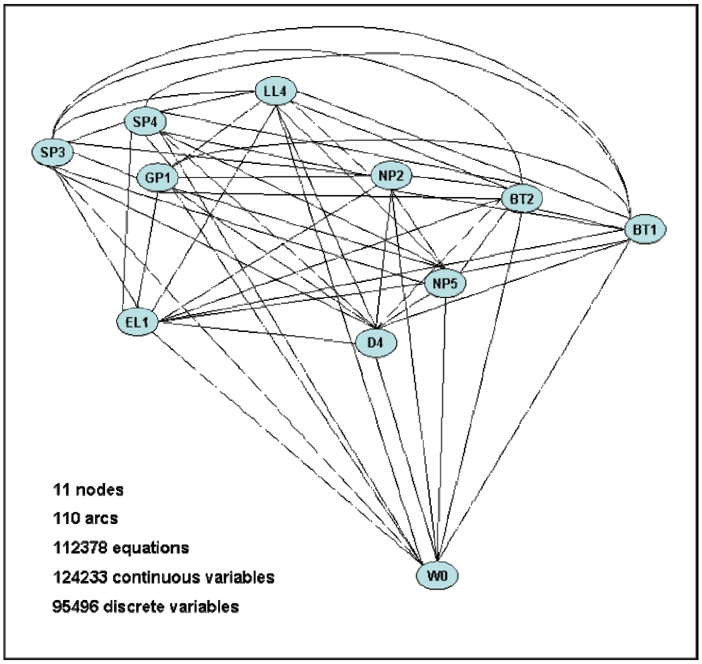


Figure 13. **Network representation for scenarios A and B after node elimination.**

### 2. Symmetry Breaking

In spite of a notable reduction in the total number of nodes, the number of arcs is still large because of the all-to-all connectivity (Figure 13). Many of those arcs are actually passing through the transition nodes that are out of sight here. Therefore, the shortest path between two demand nodes (represented as a direct arc) might be of the same distance as several arcs in the network. That causes symmetry in the model, i.e., multiple solutions in the formulation represent, in practice, the same solution. Symmetry can be avoided by extracting the replicated arcs, i.e., those arcs that represent paths (between demand nodes) that do not contain intermediate nodes only. This issue can be clarified further with the following example: Assume A, D and H are the demand nodes in the network. Remaining nodes are transition nodes. The reduced network consists of nodes A, D and H only, with arcs (A,D), (D,H) and (A,H). However, if the shortest path between A and H uses D, it will not be necessary to consider the arc between A and H (the dashed line in Figure 14, whose length would be precisely the sum of distances (A,D) plus (D,H)). On the other hand, if the shortest path from A to H does not use D, we

need to consider a direct arc from A to H. This idea will help us eliminate unnecessary arcs and reduce the size of the problem, which is especially important in large networks.

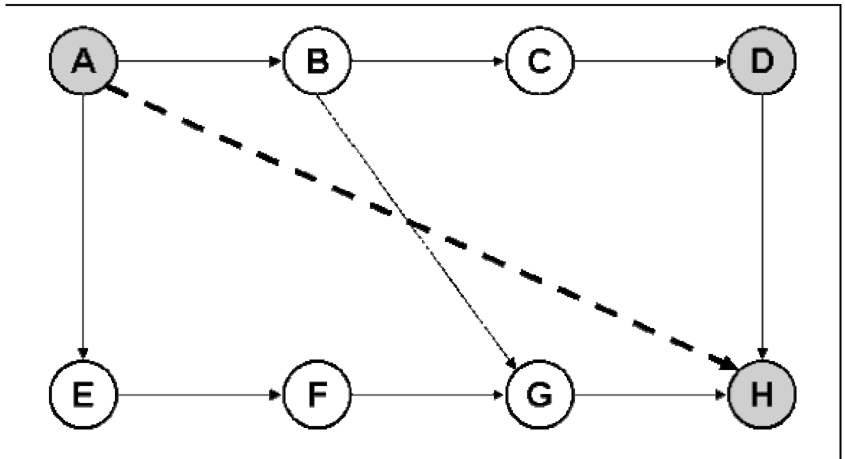


Figure 14. **Symmetry breaking**

Our symmetry breaking algorithm is depicted in Figure 15. The predecessor tree from the Floyd-Warshall algorithm is used to decide whether or not every arc in the simplified network is redundant.

For all arcs $(i,j)$ in the simplified network (i.e., network with demand nodes only and all-to-all arcs) do:

1. Let $k$ = pred$(i,j)$
2. If $k = i$, do not remove the arc$(i,j)$ from the arc list and exit
   Else if $k$ is a node in the simplified network, remove arc$(i,j)$ and exit
   Else set $j = k$ and go back to step 1.

Figure 15. **Algorithm to eliminate transition nodes and break symmetry in the simplified network.**

Figure 16 depicts the final network layout after symmetry breaking. Realize the enormous simplification made with respect to the original network in Figure 7. Accordingly, significant reduction in model size has been achieved (Figures 17 and 18). This yields considerable time saving in our computations. The next chapter discusses the results.

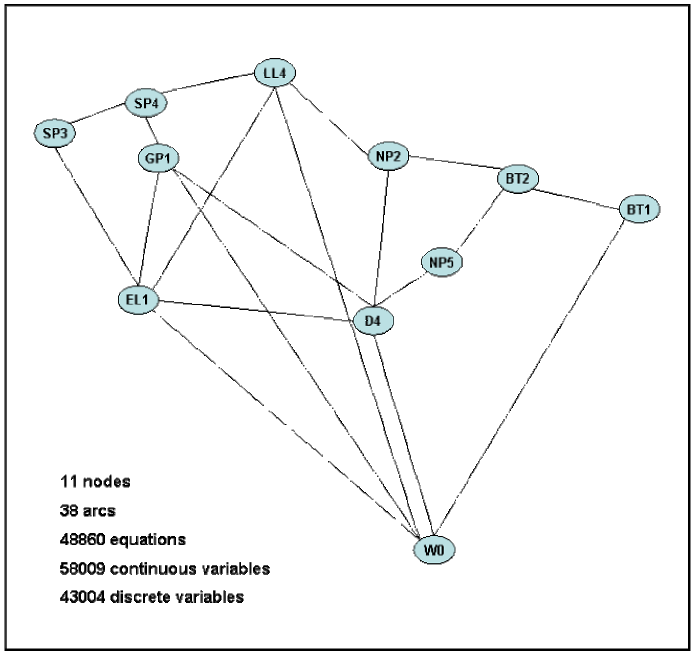


Figure 16. **Network representation for scenarios A and B after breaking the symmetry.**

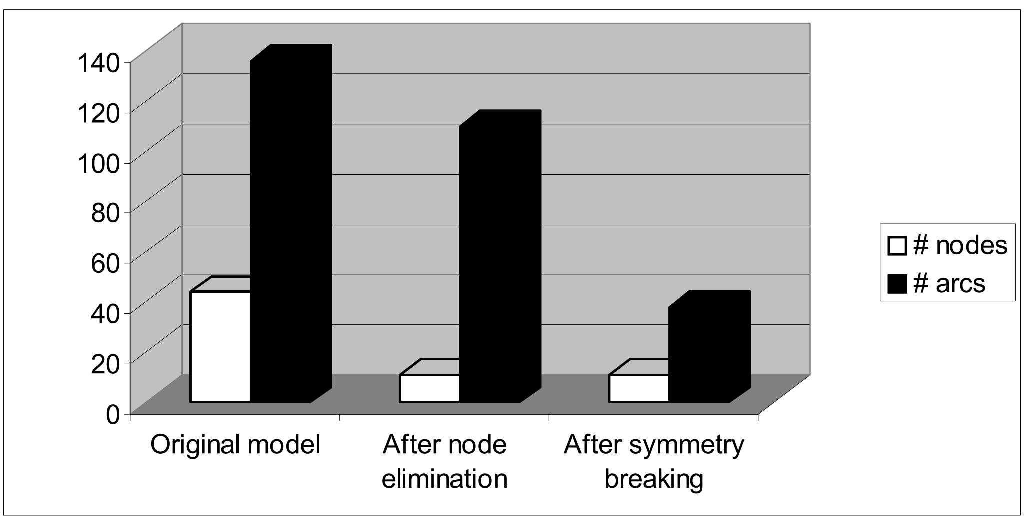


Figure 17. **Network size reduction after the specified improvements in the data structures.**

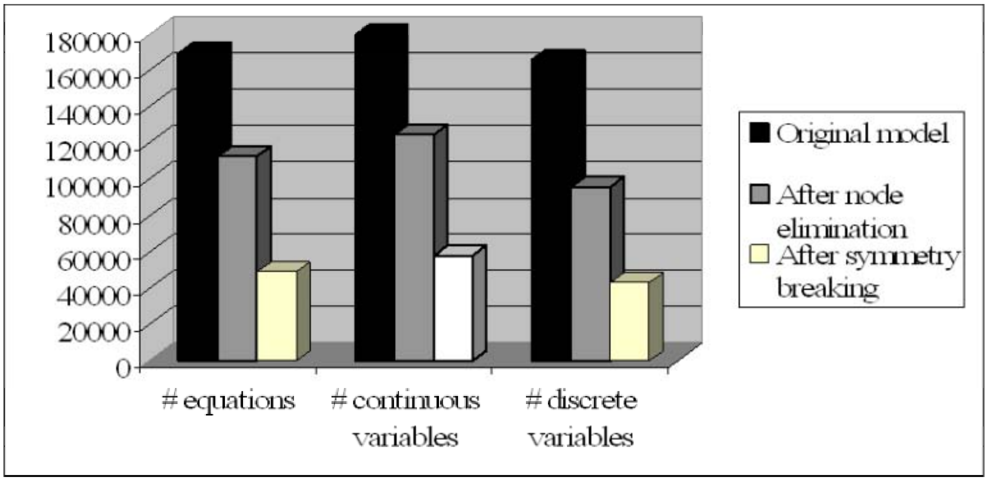


Figure 18. **Reduction in the model size after the specified improvements in the data structure.**

## C. MODEL ENHANCEMENTS

The original model allows the vehicles to be loaded at most once during a day. Every vehicle leaves the origin node, completes its delivery, and returns to the CSSE node; it cannot be reloaded and make a second delivery, regardless how much time is left in the day. For example, in Figure 19, we depict a vehicle leaving the origin at time period 2, and returning at time period 15. This vehicle waits at the origin, probably inefficiently, for the remainder of the day.

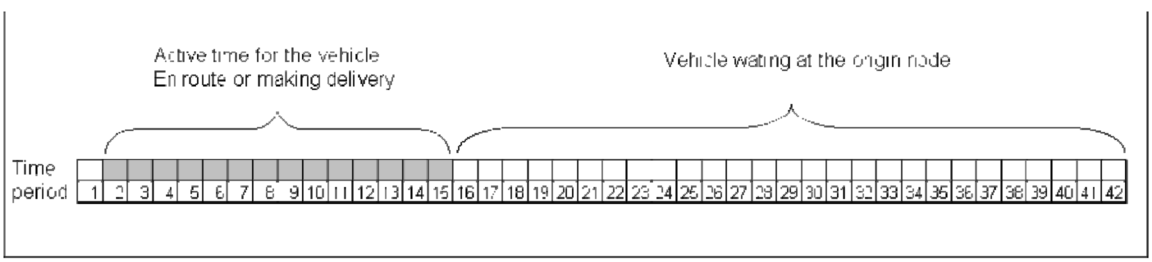


Figure 19. **Example of working and idle time periods for a vehicle after the first run**

This thesis modifies the implementation of the model to allow vehicles to make a second delivery. Conditions required for a second trip and assumptions to conduct it are as follows:

- Part of the total demand cannot be met by dispatching all the vehicles once. Unmet demand still exists at some of the nodes.

- Vacant times of the vehicles after the first delivery must fit the demand time windows of the nodes waiting for a second delivery.
- Reloading times of the vehicles are assumed to be equal to their delivery times.
- When a vehicle is back to the origin node (garage) from its first delivery, it can get refueled and take a fresh driver, if necessary. This allows us to ignore fuel and crew time constraints in the model.

The working principle of this enhancement is to run the model twice. Once the model is run for the first time, the active and reloading time periods for each vehicle are fixed to prevent it from being used again in the second run. Then, leftover demands are passed to the second run (Figure 20). The model seeks an optimal way to exploit the idle times of the vehicles (Figure 21). The influence of this improvement is more observable in the TUARM scenario due to more suitable time window distributions. In the USMC scenario, the majority of the nodes have demands between the time steps 10 and 25. Therefore, for example, vehicles with an idle time period between the time steps 25 and 42 after the first round of delivery cannot be utilized where there might still exists some unmet demand to be met between the time steps 10 and 25. The time windows in the TUARM scenario is more evenly distributed than those in the USMC scenarios. Thus, the vehicles have greater chance to find appropriate demand nodes to make their second deliveries. Results are discussed in the next chapter.

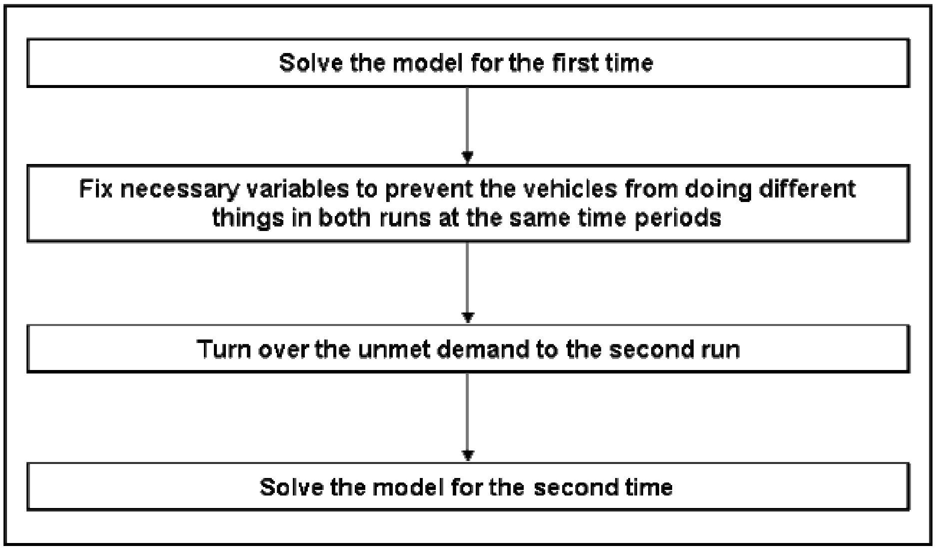


Figure 20. **Algorithm for allowing the vehicles to reload and make a second delivery**

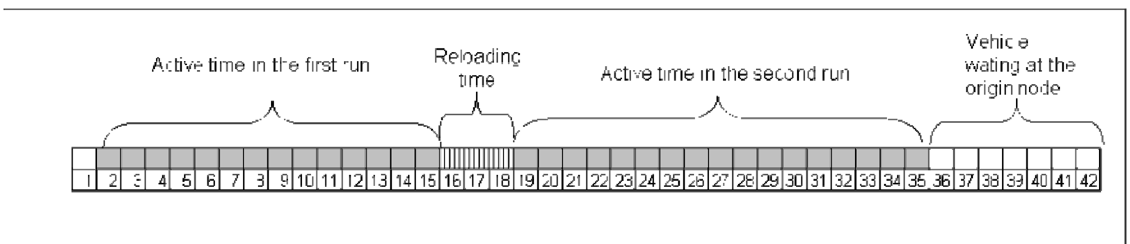


Figure 21. **Example of working and idle time periods for a vehicle after the second run**

The vehicle goes for a second delivery during its idle time and meets some demand. Model efficiency can be increased by using this approach.

Remark: An alternative way to handle reloading explicitly in the model would be to consider load balance equations for the vehicles at each time period. By adding a sub-index "$t$" to the amount of load on the vehicle ($L_{vct}$), and a new variable to represent loading (or reloading) at the origin ($R_{vct}$), we can establish a new formulation with the following constraints:

$$R_{vct} \le q_{vc} W_{v"0"t}\,, \qquad \forall v \in V, t \in T \qquad \text{(Reload-1)}$$

$$L_{vct} = L_{vc,t-1} - \sum_{i \in N} S_{vict} + R_{vct} \qquad \forall v \in V, c \in C, t \in T \qquad \text{(Reload-2)}$$

$$\sum_{c \in C} L_{vct} \le \max q_v \qquad \forall v \in V, t \in T \qquad \text{(Reload-3)}$$

The first constraint would ensure that reloading occurs at the origin node only. The second constraint is the load balance equation for each vehicle. The third equation ensures the vehicle total capacity is not exceeded at any time.

Although this formulation requires additional variables ($L_{vct}$ instead of $L_{vc}$), since these are continuous variables, it is likely that the new model can be solved almost as efficiently as the one without reloading. We have not explored this new formulation in the scope of this thesis.

# V. RESULTS

This chapter presents the results obtained from the exact and the heuristic methods. The USMC scenarios are solved before and after the improvements discussed in Chapter IV. Specifically, we focus our analysis in solution quality and computational time. Subsequently, TUARM scenario is solved and applicability of LOCCC to a Turkish Infantry Brigade is discussed. All the computations are executed on an Intel ® Pentium® 4 CPU, 2 GHz computer with 1 Gb of RAM running under Microsoft Windows 2000 operating system. The optimization models are coded in General Algebraic Modeling System (GAMS) (Brooke et al. 1998) and solved by CPLEX 9.0 (ILOG 2004).

## A. U.S. MARINE CORPS SCENARIO

Major Lenhardt built a model to explore Combat Service Support concepts. A brief summary of his conclusions is as follows:

- When a full re-supply is required by a MEB, most of the demand can be met by CSSE. If 100% support is required for a MEB, more ground transportation assets have to be added to the fleet or airlift has to be considered.
- Partial re-supply of a MEB (50% of full re-supply) can be handled by CSSE.
- CSSE is capable of meeting the demands of smaller size units such as special task forces.
- The VRP model could be improved by enhancing model realism, decreasing total unmet demand in the solution, and simplifying model structure to ensure a timelier solution.

Time is one of the most crucial elements in decision making. Decision makers are usually under time pressure to make critical decisions. Tools that are intended to facilitate the decision making should be utilized in reasonable time frames. How the node elimination and the symmetry breaking lessen the model complexity is explained in the

following sections. We demonstrate the enhancements in solving times and objective function values owing to the simplifications in model structure. The outputs show that a noteworthy enhancement is carried out after the improvements are applied to the model.

As Major Lenhardt noticed, it takes considerably long time to use the exact method. Even the heuristic with large vehicle groups requires extensive computational effort. Implementing the model in real life might be costly for that reason. (See Table 3 for results reported in Major Lenhardt's thesis.) As we will show, the solver makes quicker progress in search for an optimal solution after we apply the node elimination and the symmetry breaking strategies developed in this thesis.

Given the computer and the solver version used by Major Lenhardt were not as speedy and powerful as the ones used for this thesis, we have executed his computer code again using the same resources as for this study, in order to carry out a fair comparison and have a better understanding of the actual improvements.

### 1. Exact Method

Time limit is set to 100,000 seconds (27 hrs 47 mins) in order to keep the model from running forever. No other restrictions are imposed on CPLEX. Figures 22 through 25 show the evolution of the solution value before and after the improvements. Data tables for these figures can be found in Appendix D.

Scenario A is different from the others, because we can prove the demand can never be met with the available assets. (A valid lower bound on the optimal solution is 37.73 stons when the solver is stopped after 27 hours and 47 minutes.) The exact method is stopped after 10 hours since there was no further improvement in Major Lenhardt's thesis. It took 4 hours and 6 minutes to reach to 61.45 stons with a relative optimality gap of 55%. The single triangle in Figure 22 represents this solution. The same code has been run with a better computer and the most recent solver version. Although initially it performs slightly worse than reported by Major Lenhardt, eventually it achieves a better objective value. The best feasible integer solution is achieved after 19 hours and 52 minutes. The execution is stopped at 27 hours and 47 minutes.

Either before or after the improvements, the objective value evolves negligibly after it reaches the 50 stons mark. Considering this threshold, we observe that, after the improvements, we find this solution in 42 minutes using the fully simplified network, whereas it takes 10 hours and 36 minutes in the original network. Also from a practical point of view, if we set the maximum solve time to 10 or 15 minutes (which would be acceptable for operational purposes), we can see that the solution after improvements (approximately 75 stons of unmet demand) greatly outperforms that before the improvements (approximately 300 stons). Figure 23 presents a similar picture of the speed gained to close the relative optimality gap. Before the improvements, a relative gap under 30% is obtained in 8 hours and 17 minutes, and 10 hours and 42 minutes are required for a value below 20%. The same figures are achieved in 42 minutes, and 2 hours and 33 minutes respectively after the improvements.

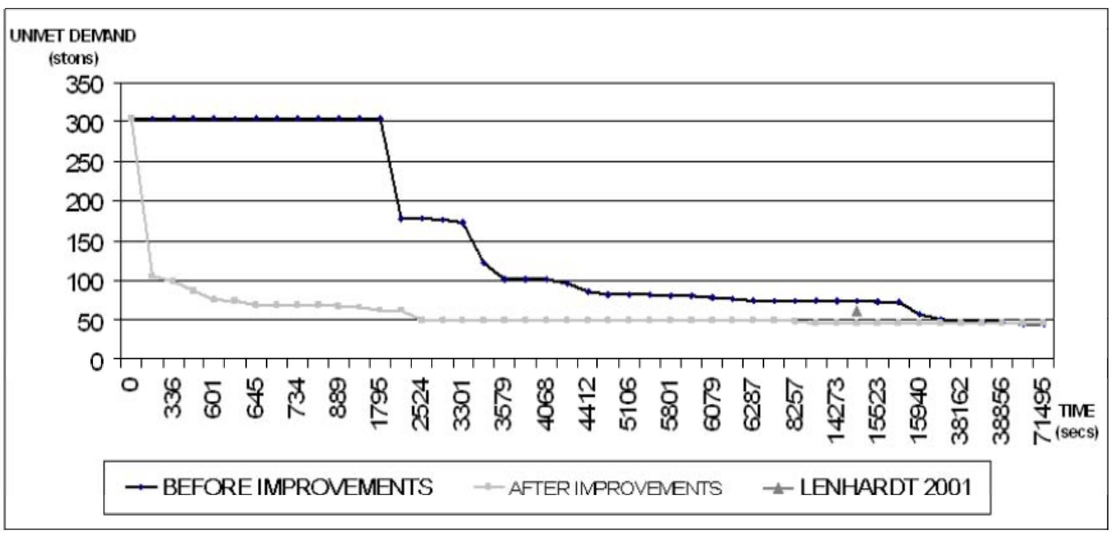


Figure 22. **Total unmet demand vs. time before and after improvements (scenario A – exact method)**

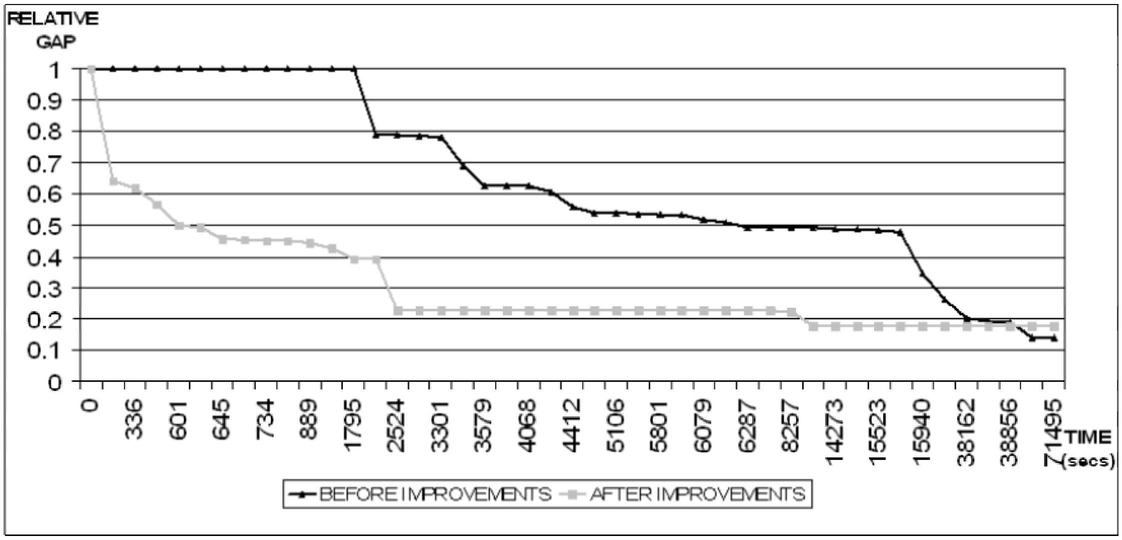


Figure 23. **Relative gap vs. time before and after improvements (scenario A – exact method)**

Gap is computed as ((UB – LB) / UB) where UB (upper bound) is the best solution found so far and LB (lower bound) is the best lower bound in the optimal solution.

The benefit of the modeling enhancements developed in this thesis is even more clear in scenarios B and C. For scenario B, it takes 4 hours and 5 minutes in Major Lenhardt's implementations in 2001 to meet all the demand. Actually all the demand is not met in this scenario, but an unmet quantity of a couple of tons is tolerable for our purposes. The same code meets all the demand in 2 hours and 57 minutes with today's computational power. After simplifying the network, it takes only 20 minutes (Figure 24).

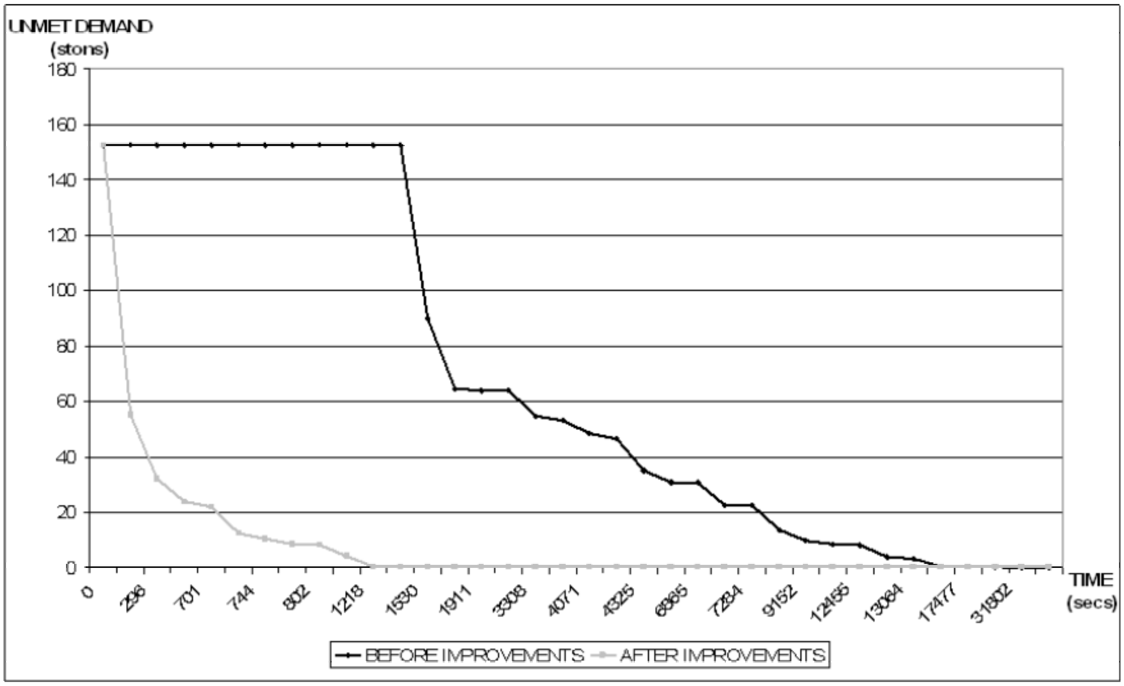


Figure 24. **Total unmet demand vs. time before and after improvements (scenario B – exact method)**

Major Lenhardt's reports 37 minutes for scenario C. The same code produced the same optimal solution in 2 hours and 42 minutes today. That difference is because of the optimality criterion defined before the model is started. CPLEX might spend enormous time to find a negligibly better solution. However, optimality criteria cannot be changed while the model is working. After the improvements, the same objective function value is obtained in 16 minutes (Figure 25).

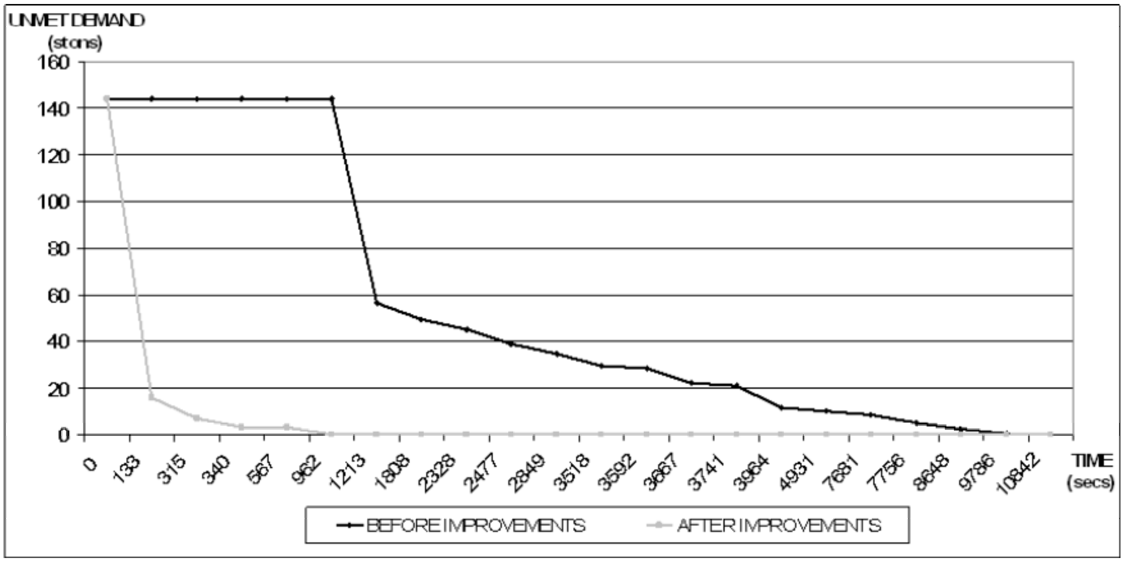


Figure 25. **Total unmet demand vs. time before and after improvements (scenario C – exact method)**

### 2. Heuristic Methods

Heuristics cannot guarantee an optimal solution, but they can be used to find a feasible solution to a problem, generally quicker than the exact method. Some limitations are applied in order to keep the total solving time reasonably small, which is the primary rationale of using heuristics. The model is limited to be solved in 15 minutes with each vehicle group, and the absolute and relative optimality gap tolerances are set to be 0.002 stons and 0.5% respectively. The codes before and after the improvements are executed, and the results are illustrated in Figures 26 through 31. Developments in the objective value show the transition among the vehicle groups.

It takes 17 minutes and 35 seconds to obtain the final feasible solution without the improvements in the heuristic by using two-vehicle groups. The same case takes only 80 seconds after the improvements with a slightly better objective function value (Figure 26). Those times are 48 minutes and 45 minutes respectively for groups of four vehicles (Figure 27). It is noteworthy that the model gets to a feasible solution during branch and bound (B&B) algorithm more quickly after the improvements are applied. The linear Programming (LP) relaxation solution for this scenario is 7.79 stons. This is the only way to assess a heuristic solution. Total unmet demand can never go below 7.79 stons for this problem. It is not known to us how close to this value the true optimal solution might be.

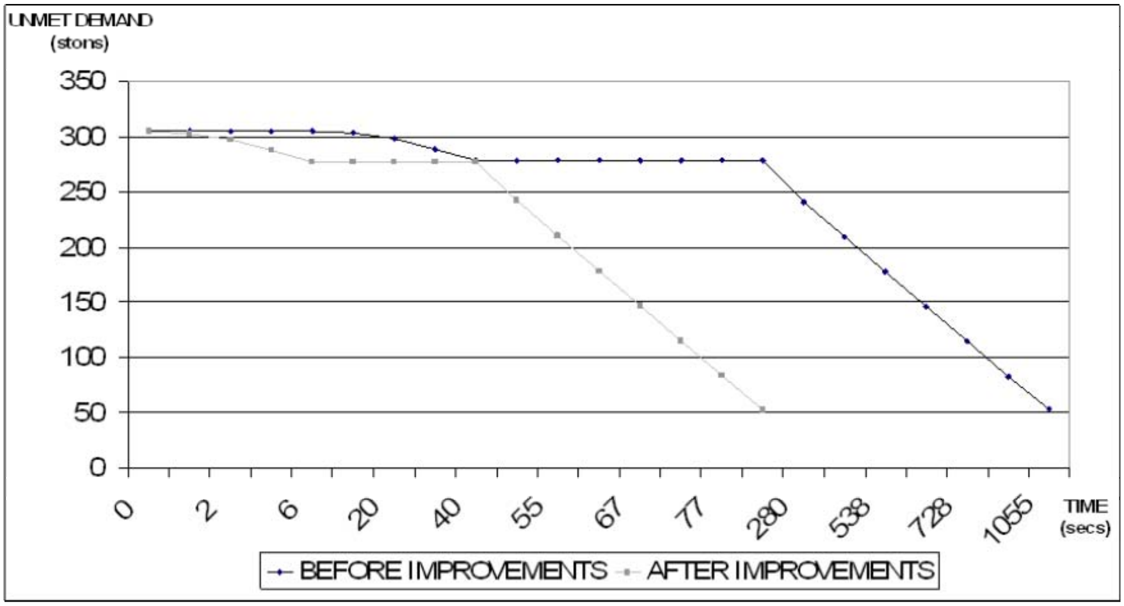


Figure 26. **Total unmet demand vs. time before and after improvements (scenario A – group size 2)**

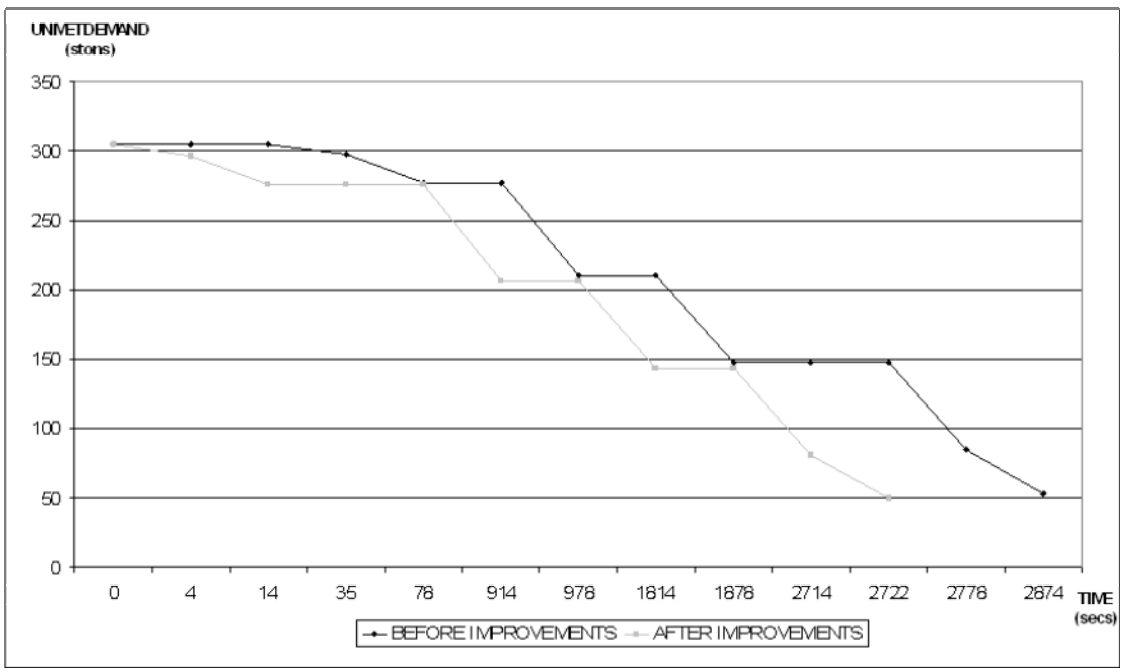


Figure 27. **Total unmet demand vs. time before and after improvements (scenario A – group size 4)**

For scenario B and two-vehicle groups, the solution is obtained in 11 minutes and 30 seconds before the improvements, whereas it takes only 59 seconds after the

improvements (Figure 28). The same results are realized in 1 hour and 1 minute, and 55 minutes respectively for groups of four vehicles (Figure 29). The entire demand is met.

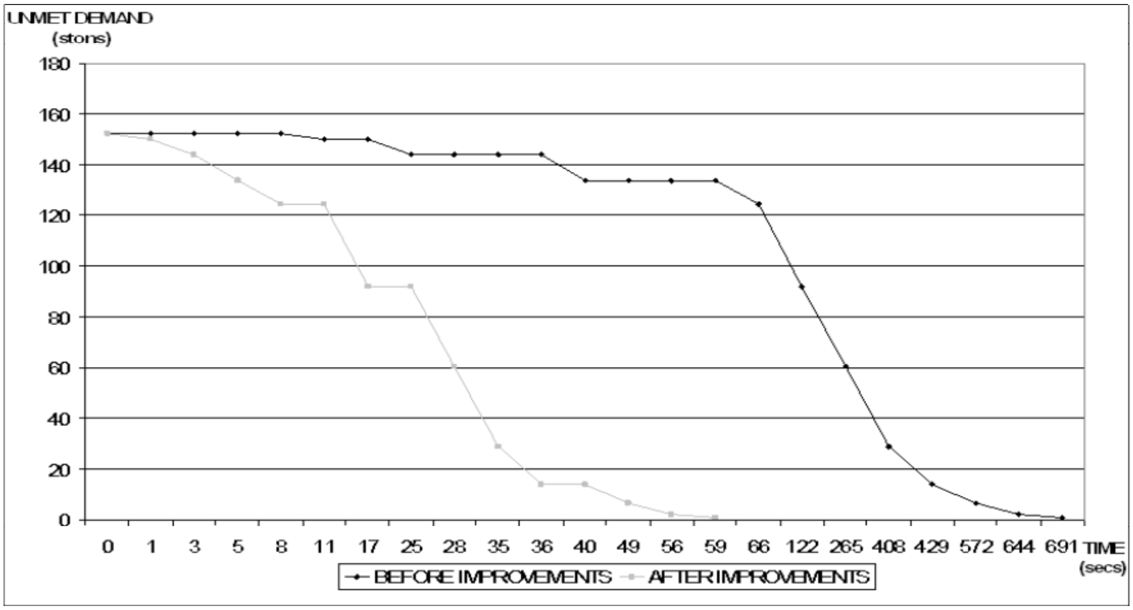


Figure 28. **Total unmet demand vs. time before and after improvements (scenario B – group size 2)**

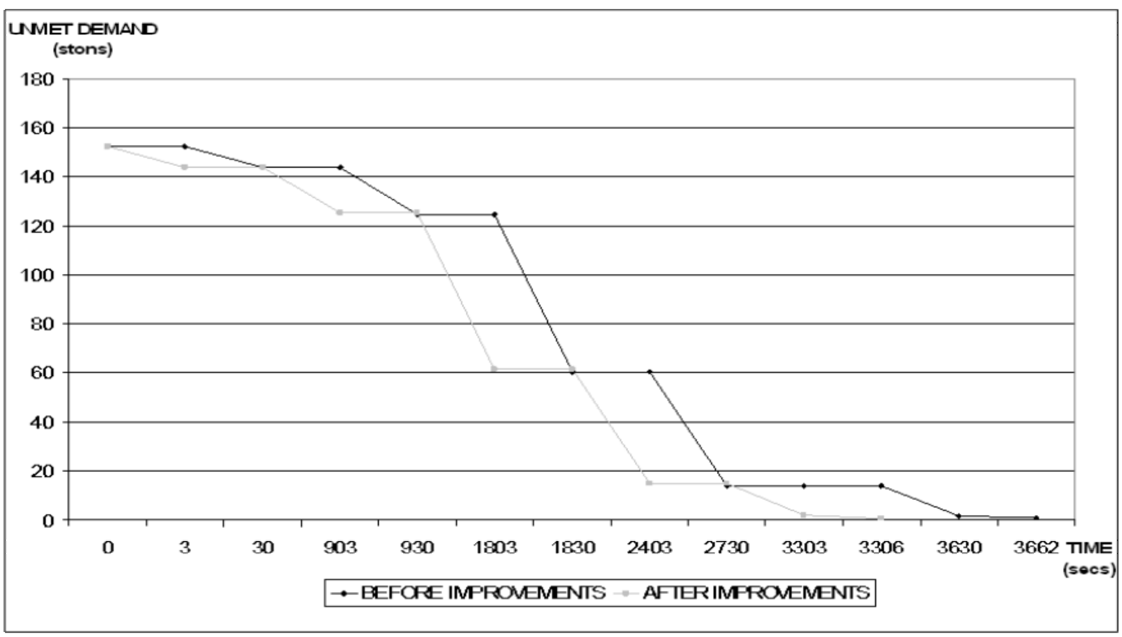


Figure 29. **Total unmet demand vs. time before and after improvements (scenario B – group size 4)**

Similar results can be seen in Figures 30 and 31 for scenario C.

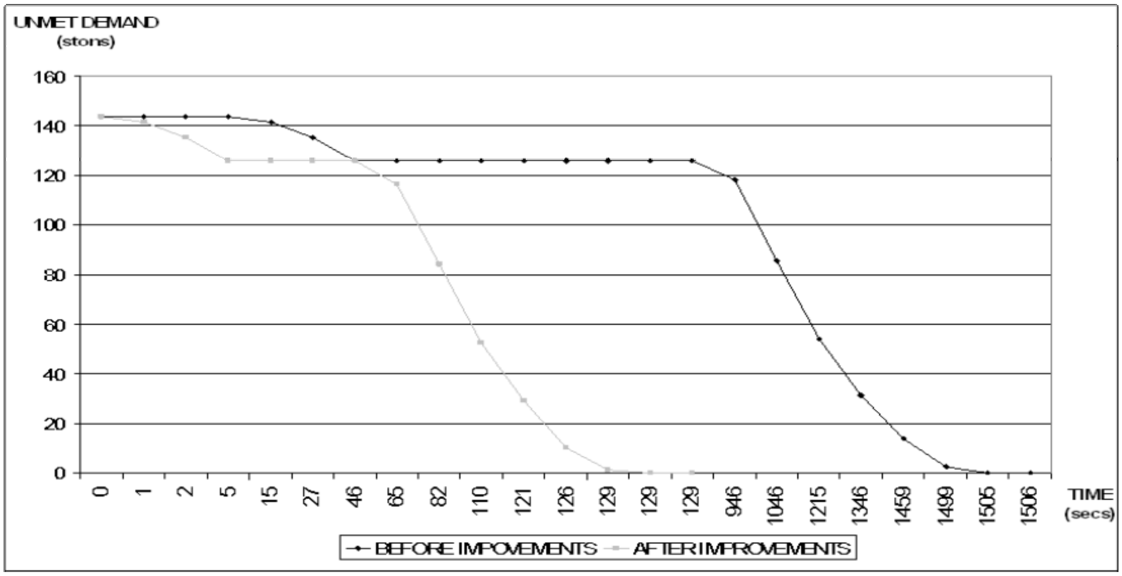


Figure 30. **Total unmet demand vs. time before and after improvements (scenario C – group size 2)**

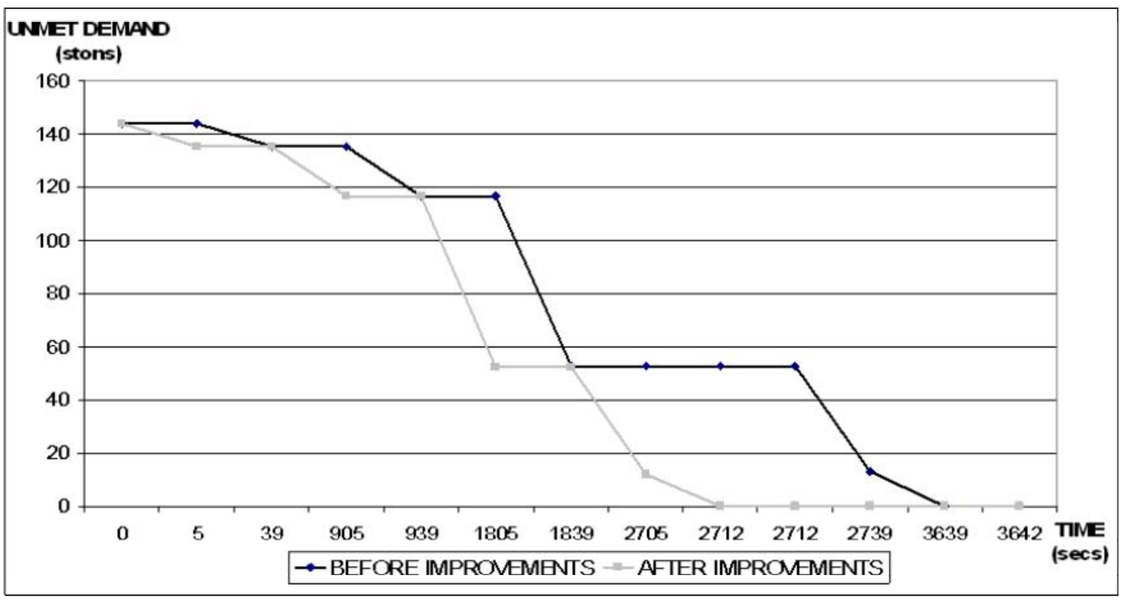


Figure 31. **Total unmet demand vs. time before and after improvements (scenario C – group Size 4)**

The solutions can be improved by using different group arrangements. A very large number of combinations are available for vehicle grouping. We only use the one that entirely reverses the order. The most notable difference between the two grouping orders is the total loading capacities in each group (Table 4).

| Forward | | Backward | |
|---|---|---|---|
| Vehicles in the group | Total loading capacity (stons) | Vehicles in the group | Total loading capacity (stons) |
| 1-2-3-4 | 8.561 | 22-21-20-19 | 80.000 |
| 5-6-7-8 | 20.000 | 18-17-16-15 | 80.000 |
| 9-10-11-12 | 80.000 | 14-13-12-11 | 80.000 |
| 13-14-15-16 | 80.000 | 10-9-8-7 | 50.000 |
| 17-18-19-20 | 80.000 | 6-5-4-3 | 16.187 |
| 21-22 | 40.000 | 2-1 | 2.374 |

Table 4. **Difference between two vehicle grouping orders in terms of total loading capacities for groups of 4 vehicles.**

No significant improvement is achieved for scenarios B and C, because they already have all the demands met, but we can see the difference in the results obtained from scenario A (Table 5). An improvement in the objective function (6.2 stons or 13%) emerges as the solving time increases 32 seconds (40%) for two-vehicle groups. For four-vehicle groups, however, the improvement gained in the objective value is 4.3 stons (9%), which does not seem to offset the extra 1,778 seconds (67%) needed to achieve this result.

| Group Size | Grouping order | Total Unmet Demand (stons) | Resource Usage Time (secs) |
|---|---|---|---|
| 2 | Forward | 52.420 | 80.854 |
| 2 | Backward | 46.248 | 113.307 |
| 4 | Forward | 49.718 | 2722.405 |
| 4 | Backward | 45.428 | 4500.000 |

Table 5. **Differences of the results between grouping orders for scenario A.**

As explained in Section IV.C, an enhancement in the model specification is to allow suitable vehicles to make a second delivery after reloading and refueling at the origin node. We utilize two-vehicle groups for both deliveries in order to keep the computation time minimum, and test scenario A. (Notice the entire demand is met during the first delivery in the other two scenarios.) We use the heuristic strategy discussed in Section IV.C that allows trucks to make a second delivery, if they have enough idle time

at the CSSE node. Vehicle groups are dispatched in the algorithm from the last to the first. The contribution of the second delivery is not very noticeable in this scenario, because vehicles are busy with the first delivery for most of the day, and their limited idle times at the origin node do not fit with required delivery time windows of the units. The first round of deliveries takes 113.53 seconds of solving time and the total unmet demand is 46.25 stons. Only one vehicle is able to make a second delivery of 1 ston, reducing the total unmet demand to 45.25 stons (Figure 32). Other vehicles are not able to meet any demand within their idle time frames. The contribution of second deliveries is more effective in TUARM scenario, as we show in the next section.

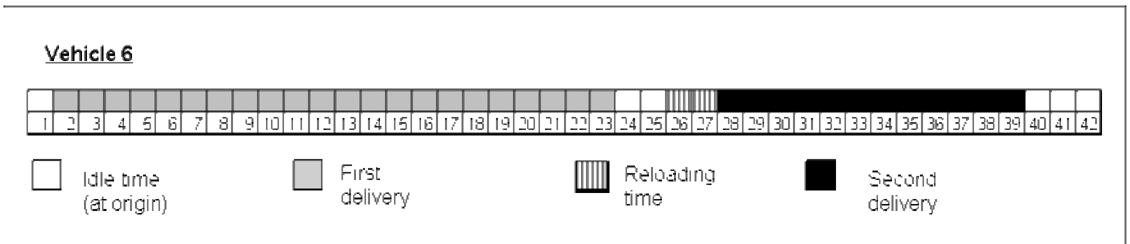


Figure 32. **Timeline showing idle and working times of vehicles that are capable of making a second delivery in USMC scenario A.**

## B. TURKISH ARMY SCENARIO

This scenario employs more transportation assets than the USMC scenario. That means a big swell in the total number of variables and equations. Hence, the model becomes more complex, with 379,016 equations and 768,965 decision variables (even after the improvements are applied). Despite the node elimination and the symmetry breaking improvements, it still takes an exceptionally long time to solve the model with the exact method. The model was interrupted at 27 hours and 47 minutes (100,000 seconds), but the quantity of delivery was still less than 25% of the total requested demand, and the solver was still keeping a zero lower bound. Heuristics of various group sizes have been executed. The most myopic heuristic (single vehicle in each group) has been tried in addition to two and four-vehicle groups. No considerable differences exist among the objective function values of different heuristics. However, solution times vary substantially (Table 6). The solver is subject to the same limitations as in the USMC scenario, such as a time limit of 15 minutes for each vehicle group, and relative and

absolute optimality gaps of 0.5% and 0.02 tons, respectively, for each problem solved in the heuristic.

| INITIAL DEMAND = 208.24 stons | | | |
|---|---|---|---|
| Group size | Grouping order | Computation time (secs) | Unmet demand (stons) |
| 1 | Forward | 129 | 19.09 |
| 1 | Backward | 110 | 18.36 |
| 2 | Forward | 1101 | 22.54 |
| 2 | Backward | 822 | 17.41 |
| 4 | Forward | 351 | 19.32 |
| 4 | Backward | 378 | 24.21 |

Table 6. **Differences of the results among group sizes and orders**

The heuristic with one-vehicle groups provides a satisfactory solution in acceptable time: Total unmet demand is less than 9% of total. However, the LP relaxation of the full problem is zero, therefore we cannot tell how far these values are from the true optimal. Solution times with larger groups increases notably while they produce either negligible or no improvements in the total unmet demand. We conclude that a Turkish Infantry Brigade can be basically supplied with its own transportation assets (available trucks, tankers and trailers in the quartermaster and ordnance companies). The demand that is still unmet after the first round of delivery can still be met by allowing reloading of some trucks: One-vehicle groups are used in backwards dispatching order. The first delivery round is solved in 110 seconds, and the amount of unmet demand turned over to the second round of trips is 18.36 tons. We take advantage of idle times as depicted in Figure 33. Fourteen vehicles are used for a second delivery, and eventually all the demand in the network is met. The reloading capability enables us to meet all the demand without using any additional assets.

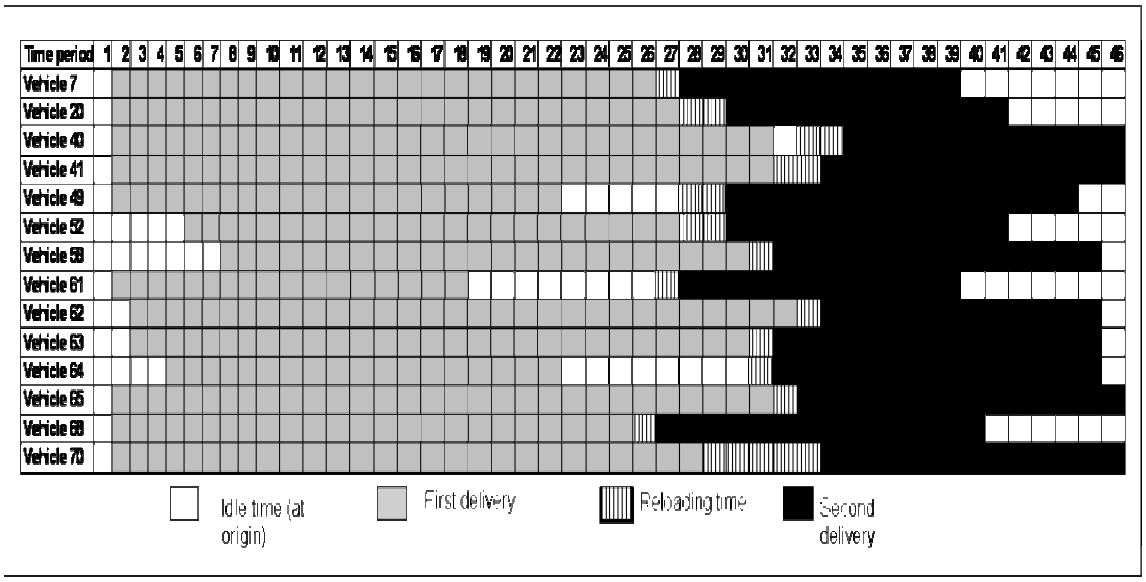


Figure 33. **Timeline showing idle and working times of vehicles that are capable of reloading and making a second round of trips in TUARM scenario.**

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# VI. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

We adopt Major Lenhardt's optimization model (Lenhardt, 2001) to represent the LOCCC concept. We revisit the data structures embedded in his mathematical models and algorithms. By making some simplifications and enhancements in these structures, we demonstrate the resulting networks are computationally tractable with the existing models, while still maintaining all the necessary information required to devise an optimal distribution schedule.

We show that the simplifications and enhancements achieved in this thesis lead to a significant improvement in solving time. For example, in a ten-minute run, we can obtain a solution that is 98% better in some cases.

We also test the model to a Turkish Infantry Brigade by using its own sustainment requirements and transportation assets. The results show us that the LOCCC concept can be applied in this scenario, although the computational effort is substantially higher than that of the USMC scenarios.

Furthermore, we incorporate reloading in the problem, in order to enhance its realism. This allows us to improve our solution by 2% in some cases of the USMC scenario and meet the entire demand in the Turkish Army scenario.

Further analyses may improve the model to achieve more realism and reduce its complexity. Some possible research opportunities to follow this study are as follows:

- For a logistics planner, having a delivery at the required time and place is essential. In the current model, a time index (representing a 20-minute interval) is associated with most variables and constraints, which increases the size and difficulty of the model. A possible enhancement would consist of monitoring how many times a vehicle delivers before going back to the CSSE node. By doing so, time indices can be replaced by delivery sequence indices on the variables. Variable numbers would be reduced and the model would become less complex.

- The CPLEX solver cannot be interrupted to modify the searching criteria of the B&B algorithm. For example, optimality criteria have to be initially set. B&B sometimes spends an excessive amount of time at a feasible solution without improving it. It might be reasonable to accept a "close enough" solution to predefined optimality criteria if we have already spent much time in improving such solution unsuccessfully. Xpress-Mosel, an advanced optimization language developed by Dash Optimization (Dash, 2005), can be used to overcome this problem by using callbacks that give full control over the B&B process.

- Transportation assets are assumed to have no mechanical failures. Real data from previous combats or exercises can be analyzed to get expected failure rates for the vehicles. The model can be more realistic if vehicle malfunctions are represented.

- In the current model, the branching strategy assigns higher priorities to units with higher demands. A future study can assign priorities according to the tactical importance of the units.

- Time and network resolution can be augmented, e.g., time can be divided into smaller intervals of 5 or 10 minutes.

- The solution of USMC scenario A can be improved and, hopefully, finalized. When the solver is interrupted after 100,000 seconds, the lower bound is 37.73 stons and the best solution is 45.96 stons. The heuristic with four-vehicle groups can already achieve a better solution (45.24 stons) when the vehicle groups are dispatched backwards. However, the true optimal solution to this problem is, as of now, unknown. Similarly, we do not know if there is a way to meet the entire demand in the TUARM scenario without reloading the vehicles.

- Reloading and redelivering can be explicitly implemented in the model by adding proposed equations in Section IV.C. This would embed the concept

in the formulation, instead of myopically solving the model without reloading and then allow reloading for idle vehicles.

- In those cases where entire demand can be met, there might be multiple ways to achieve it. New goals can be incorporated in the model to solve it more effectively. For example, meeting all demand by using the least possible number of trucks.

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# APPENDIX A. ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| B&B | Branch and Bound |
| CSSD | Combat Service Support Detachment |
| CSSE | Combat Service Support Element |
| FSSG | Force Service Support Group |
| FTON | Five Ton (A vehicle type used in the USMC scenario) |
| GAMS | General Algebraic Modeling System |
| GS | General Support |
| HMMWV | High Mobility Multipurpose Wheeled Vehicle (A vehicle type used in the USMC scenario) |
| LOCCC | Logistics Operations Command and Control Capability |
| LP | Linear Programming |
| LVS | Logistics Vehicle System (A vehicle type used in the USMC scenario) |
| MAGTF | Marine Air Ground Task Force |
| MCSSD | Mobile Combat Service Support Detachment |
| MCWP | Marine Corps Warfighting Publication |
| MEB | Marine Expeditionary Brigade |
| MEF | Marine Expeditionary Force |
| MRE | Meal Ready to Eat |
| POL | Petroleum, Oil, and Lubricant |
| ston | Short Ton |
| TUARM | Turkish Army |
| USMC | United States Marine Corps |
| VRP | Vehicle Routing Problem |

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# APPENDIX B. FLOYD – WARSHALL ALGORITHM

The Floyd-Warshall algorithm (Ahuja et al., 1993) is a shortest path algorithm to find the shortest routes and distances between every possible node pairs in a network. The algorithm produces distance and predecessor matrices. The distance matrix gives us the distance between each node pair. The predecessor matrix is used to track the nodes along the shortest route between two nodes (from the sink to the source, tracking backwards). The algorithm below is from Ahuja et al. (1993):

N: Set of nodes

A: Set of arcs

pred[i,j]: The node preceding "j" on the way from "i" to "j"

d[i,j]: Shortest distance between nodes "i" and "j" after label correction

$c_{ij}$: Distance between nodes "i" and "j"

n: Cardinality of N

**begin**
    **for** all node pairs [i,j] $\in$ NxN **do**
            d[i,j] : = $\infty$ and pred[i,j] := 0;
    **for** all nodes i $\in$ N **do** d[i,j] := 0;
    **for** each arc (i,j) $\in$ A **do** d[i,j] := $c_{ij}$ and pred[i,j] := i;
    **for** each k := 1 to n **do**
        **for** each [i,j] $\in$ NxN **do**
            **if** d[i,j] > d[i,k] + d[k,j] **then**
            **begin**
                d[i,j] := d[i,k] + d[k,j];
                pred [i,j] := pred [k,j];
            **end;**
**end;**

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# APPENDIX C. SCENARIO MAPS AND DATA

## A. U.S. MARINE CORPS SCENARIO

This scenario is taken from Lenhardt (2001). More elaborate information about the data and scenario is available in that study.

Chapter III (Figures 7 and 8) provides the road network with distances, time windows, and unit locations for all three sub-scenarios. Those figures can be used as an overlay to the map shown in Figure 34.

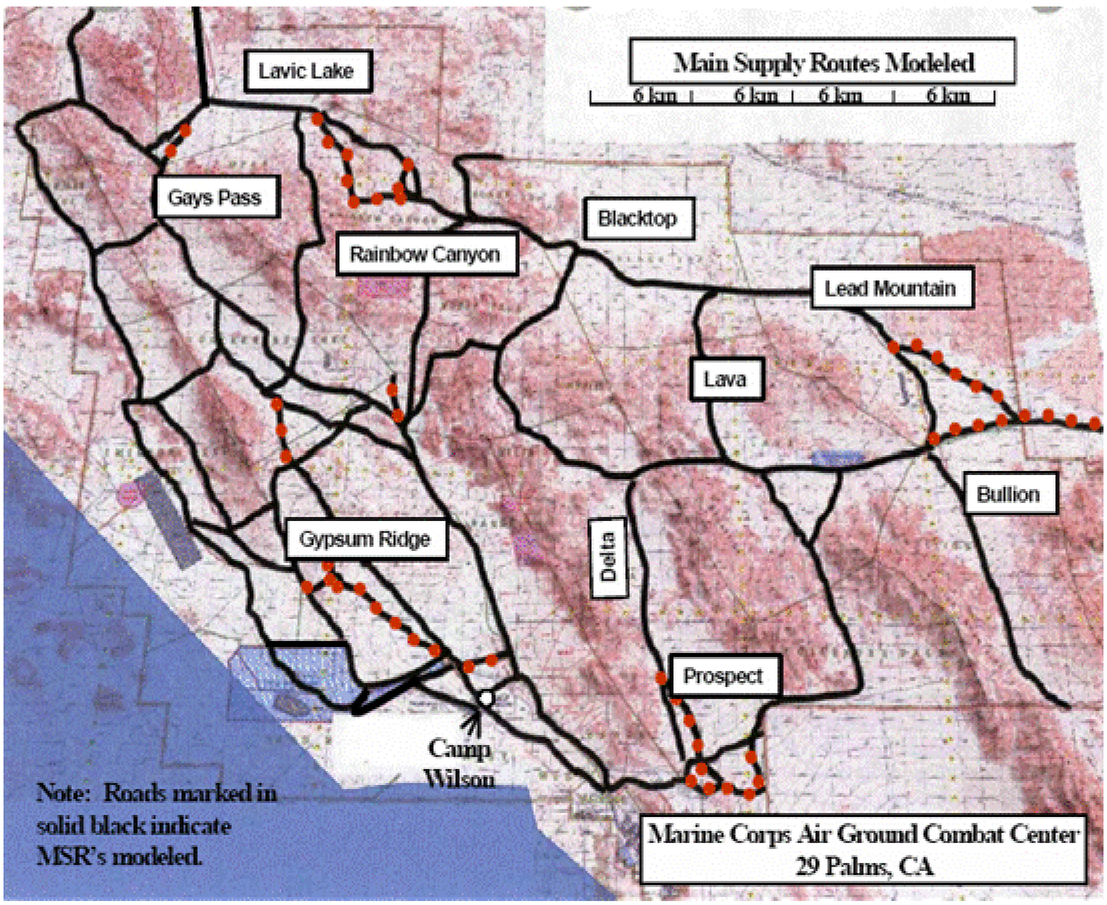


Figure 34. **Map for the USMC scenario (From Lenhardt, 2001)**

Sustainment requirements are derived from LOG2000, which is a spreadsheet model developed by Neita Armstrong (Armstrong, 2000). Details about the calculation of sustainment requirements are available from Lenhardt (2001). Demand summaries in each scenario are displayed in Tables 7-9.

| Vicinity of Demand Zone | Units | # | PAX | Supply Class Requirements (stons) MRE | Water | Fuel | Ammo |
|---|---|---|---|---|---|---|---|
| Sunshine Peak (SP3) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| | | **Total:** | 546 | **0.00** | **0.00** | **0.23** | **0.61** |
| Sunshine Peak (SP4) | Inf HQ/Wpns | 2 | 852 | 0.00 | 0.00 | 5.75 | 1.66 |
| | | **Total:** | 852 | **0.00** | **0.00** | **5.75** | **1.66** |
| Lavic Lake (LL4) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| | | **Total:** | 546 | **0.00** | **0.00** | **0.23** | **0.61** |
| Gays Pass (GP1) | Arty Btry | 2 | 294 | 0.00 | 4.75 | 23.60 | 11.56 |
| | | **Total:** | 294 | **0.00** | **4.75** | **23.60** | **11.56** |
| Emerson Lake (EL1) | AAV Co | 3 | 588 | 1.64 | 9.50 | 52.18 | 1.66 |
| | AAV HQ Co | 1 | 368 | 1.03 | 5.94 | 16.71 | 5.30 |
| | | **Total:** | 956 | **2.67** | **15.44** | **68.89** | **6.96** |
| Noble Pass (NP2) | Inf HQ/Wpns | 1 | 426 | 0.00 | 0.00 | 2.87 | 0.83 |
| | | **Total:** | 426 | **0.00** | **0.00** | **2.87** | **0.83** |
| Black Top (BT2) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.23 | 0.61 |
| | | **Total:** | 546 | **0.00** | **0.00** | **0.23** | **0.61** |
| Noble Pass (NP5) | Arty Btry | 1 | 147 | 0.00 | 2.37 | 11.80 | 5.78 |
| | | **Total:** | 147 | **0.00** | **2.37** | **11.80** | **5.78** |
| Black Top (BT1) | Tank Co | 3 | 258 | 0.72 | 4.17 | 47.48 | 1.52 |
| | Tank HQ Co | 1 | 346 | 0.96 | 5.58 | 11.42 | 0.56 |
| | LAR Co | 1 | 139 | 0.39 | 2.24 | 4.26 | 1.22 |
| | | **Total:** | 743 | **2.07** | **11.99** | **63.16** | **3.30** |
| Delta (D4) | Engr Co | 1 | 114 | 0.32 | 1.84 | 0.76 | 2.28 |
| | Engr HQ | 1 | 281 | 0.79 | 4.54 | 25.29 | 0.70 |
| | Arty Bn HQ | 1 | 139 | 0.00 | 2.25 | 6.59 | 0.10 |
| | Inf Reg HQ | 1 | 214 | 0.60 | 3.46 | 6.79 | 0.56 |
| | | **Total:** | 748 | **1.71** | **12.09** | **39.43** | **3.64** |
| | | **Grand Total:** | 5804 | 6.45 | 46.64 | 216.19 | 35.56 |
| | | | | **Total Demand:** 304.84 | | | |

Table 7. **Summary of sustainment requirements for scenario A (From Lenhardt, 2001).**

| | | | | Supply Class Requirements (stons) | | | |
|---|---|---|---|---|---|---|---|
| **Vicinity of Demand Zone** | **Units** | **#** | **PAX** | **MRE** | **Water** | **Fuel** | **Ammo** |
| Sunshine Peak (SP3) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| | | **Total:** | 546 | **0.00** | **0.00** | **0.12** | **0.31** |
| Sunshine Peak (SP4) | Inf HQ/Wpns | 2 | 852 | 0.00 | 0.00 | 2.88 | 0.83 |
| | | **Total:** | 852 | **0.00** | **0.00** | **2.88** | **0.83** |
| Lavic Lake (LL4) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| | | **Total:** | 546 | **0.00** | **0.00** | **0.12** | **0.31** |
| Gays Pass (GP1) | Arty Btry | 2 | 294 | 0.00 | 2.38 | 11.80 | 5.78 |
| | | **Total:** | 294 | **0.00** | **2.38** | **11.80** | **5.78** |
| Emerson Lake (EL1) | AAV Co | 3 | 588 | 0.82 | 4.75 | 26.09 | 0.83 |
| | AAV HQ Co | 1 | 368 | 0.52 | 2.97 | 8.36 | 2.65 |
| | | **Total:** | 956 | **1.34** | **7.72** | **34.45** | **3.48** |
| Noble Pass (NP2) | Inf HQ/Wpns | 1 | 426 | 0.00 | 0.00 | 1.44 | 0.42 |
| | | **Total:** | 426 | **0.00** | **0.00** | **1.44** | **0.42** |
| Black Top (BT2) | Inf Co | 3 | 546 | 0.00 | 0.00 | 0.12 | 0.31 |
| | | **Total:** | 546 | **0.00** | **0.00** | **0.12** | **0.31** |
| Noble Pass (NP5) | Arty Btry | 1 | 147 | 0.00 | 1.19 | 5.90 | 2.89 |
| | | **Total:** | 147 | **0.00** | **1.19** | **5.90** | **2.89** |
| Black Top (BT1) | Tank Co | 3 | 258 | 0.36 | 2.09 | 23.74 | 0.76 |
| | Tank HQ Co | 1 | 346 | 0.48 | 2.79 | 5.71 | 0.28 |
| | LAR Co | 1 | 139 | 0.20 | 1.12 | 2.13 | 0.61 |
| | | **Total:** | 743 | **1.04** | **6.00** | **31.58** | **1.65** |
| Delta (D4) | Engr Co | 1 | 114 | 0.16 | 0.92 | 0.38 | 1.14 |
| | Engr HQ | 1 | 281 | 0.40 | 2.27 | 12.65 | 0.35 |
| | Arty Bn HQ | 1 | 139 | 0.00 | 1.13 | 3.30 | 0.05 |
| | Inf Reg HQ | 1 | 214 | 0.30 | 1.73 | 3.40 | 0.28 |
| | | **Total:** | 748 | **0.86** | **6.05** | **19.72** | **1.82** |
| | | **Grand Total:** | 5804 | 3.23 | 23.32 | 108.095 | 17.78 |
| | | | | **Total Demand:** 152.42 | | | |

Table 8. **Summary of sustainment requirements for scenario B (From Lenhardt, 2001).**

| | Supply Class Requirements (stons) | | | |
|---|---|---|---|---|
| **Vicinity of Demand Zone** | **MRE** | **Water** | **Fuel** | **Ammo** |
| Black Top (BT1) | 1.00 | 5.50 | 25.00 | 2.60 |
| Delta (D1) | 0.30 | 1.70 | 8.00 | 0.70 |
| Noble Pass (NP5) | 1.20 | 6.90 | 27.00 | 3.20 |
| Lavic Lake (LL4) | 0.40 | 2.20 | 10.00 | 1.00 |
| Gays Pass (GP1) | 0.50 | 2.60 | 13.00 | 1.20 |
| Quackenbush Lake (QL3) | 0.40 | 2.10 | 9.00 | 0.90 |
| Emerson Lake (EL1) | 0.50 | 2.70 | 13.00 | 1.25 |
| **Total Demand:** 143.85 | | | | |

Table 9. **Summary of sustainment requirements for scenario C (From Lenhardt, 2001).**

## B. TURKISH ARMY SCENARIO

The road network for this scenario is depicted in Chapter III. The map below shows the actual terrain on which the scenario takes place. It covers Trace Region in Northwestern Turkey (Figure 35).

Figure 35. **Map for the TUARM scenario**

The artillery units do not exist in the original scenario. The author adds them to tactically appropriate locations. The documents defining the unit characteristics such as personnel numbers and tasks, equipment quantities and specifications, and unit formations are classified. For this reason, estimates and assumptions are used for those characteristics. Logistics Factors and tables to make the computations below are derived from the KKT 54-5 Turkish Army Logistics Factors Manual.

Food is consumed as MREs and weighs 1.91 kg/person/day. Weather conditions are assumed to be normal, so water consumption is 53 lt/person/day. A liter of water weighs 0.982 kg, so total water consumed is computed as 52.046 kg/person/day. Water can be carried in 5-gallon barrels or tankers tailored for that purpose. Terrain features and type of the operation affect the POL consumption rate. The daily POL requirement is 9.022 lt/person/day. Factors of 1.2 for the terrain (moderate smoothness) and 1.5 for operation type (defensive) are considered in the calculation. A liter of diesel POL weighs 0.84 kg, so the total heaviness of PLO is 13.641 kg/person/day. PLO can be carried in five or 55-gallon barrels and tankers. Two different planning factors for ammunition consumption are available depending on the characteristics of the operation. We assumed the average of them for calculation purposes. By doing so, we assume the ammunition required is 13.525 kg/person/day.

| | | | | Supply Class Requirements (tons) | | | |
|---|---|---|---|---|---|---|---|
| **Demand Zone** | **Units** | **#** | **PAX** | **MRE** | **Water** | **Fuel** | **Ammo** |
| 6 | Arty Batt. | 1 | 116 | 0.22 | 6.04 | 1.58 | 1.57 |
| 11 | Arty Batt. | 2 | 232 | 0.44 | 12.07 | 3.16 | 3.14 |
| 14 | Tank Co. | 4 | 432 | 0.83 | 22.48 | 5.89 | 5.84 |
| 16 | Tank Co. | 4 | 432 | 0.83 | 22.48 | 5.89 | 5.84 |
| | HQ Co. | 1 | 224 | 0.43 | 11.66 | 3.06 | 3.03 |
| | Signal Co. | 1 | 120 | 0.23 | 6.25 | 1.64 | 1.62 |
| | Engineer Co. | 1 | 183 | 0.35 | 9.52 | 2.50 | 2.48 |
| | **TOTAL:** | | 959 | 1.83 | 1.83 | 49.91 | 13.08 |
| 26 | Infantry Co. | 1 | 153 | 0.29 | 7.96 | 2.09 | 2.07 |
| 27 | Tank Co. | 1 | 108 | 0.21 | 5.62 | 1.47 | 1.46 |
| 28 | Infantry Co. | 1 | 153 | 0.29 | 7.96 | 2.09 | 2.07 |
| 30 | Infantry Co. | 1 | 153 | 0.29 | 7.96 | 2.09 | 2.07 |
| 31 | Infantry Co. | 1 | 153 | 0.29 | 7.96 | 2.09 | 2.07 |
| 32 | Tank Co. | 1 | 108 | 0.21 | 5.62 | 1.47 | 1.46 |
| | **Grand Total:** | | 2567 | 4.90 | 4.90 | 133.60 | 35.02 |

Table 10. **Summary of sustainment requirements for the TUARM scenario.**

# APPENDIX D. COMPUTATIONAL RESULTS

Computational results are graphically displayed in Chapter V. The tables presented in this appendix provide the numerical basis for those graphs. For the exact methods, the only bound imposed on the model is the solving time (set to 100,000 seconds). For heuristic implementations, the maximum solution time is 15 minutes at every heuristic iteration and the absolute and relative optimality gap tolerances are set to be 0.002 stons and 0.5%, respectively.

## A. U.S. MARINE CORPS SCENARIO

| **Before improvements** | | | | **After improvements** | | | |
|---|---|---|---|---|---|---|---|
| **Time (secs)** | **Best integer (stons)** | **Best node (stons)** | **Gap** | **Time (secs)** | **Best integer (stons)** | **Best node (stons)** | **Gap** |
| 0 | 304.84 | 11.01 | 1.00 | 0 | 304.84 | 11.01 | 1.00 |
| 2051 | 178.33 | 37.73 | 0.79 | 314 | 105.22 | 37.73 | 0.64 |
| 3162 | 177.48 | 37.73 | 0.79 | 336 | 98.99 | 37.73 | 0.62 |
| 3301 | 172.71 | 37.73 | 0.78 | 557 | 87.04 | 37.73 | 0.57 |
| 3440 | 121.73 | 37.73 | 0.69 | 601 | 75.29 | 37.73 | 0.50 |
| 3579 | 101.05 | 37.73 | 0.63 | 623 | 74.68 | 37.73 | 0.49 |
| 3995 | 100.98 | 37.73 | 0.63 | 645 | 69.48 | 37.73 | 0.46 |
| 4273 | 95.98 | 37.73 | 0.61 | 690 | 69.21 | 37.73 | 0.45 |
| 4412 | 85.60 | 37.73 | 0.56 | 734 | 68.75 | 37.73 | 0.45 |
| 4968 | 82.21 | 37.73 | 0.54 | 745 | 68.73 | 37.73 | 0.45 |
| 5107 | 81.83 | 37.73 | 0.54 | 889 | 67.84 | 37.73 | 0.44 |
| 5523 | 81.38 | 37.73 | 0.54 | 1508 | 65.71 | 37.73 | 0.43 |
| 5801 | 81.00 | 37.73 | 0.53 | 1795 | 62.02 | 37.73 | 0.39 |
| 6079 | 78.64 | 37.73 | 0.52 | 2524 | 48.80 | 37.73 | 0.23 |
| 6218 | 77.00 | 37.73 | 0.51 | 4068 | 48.80 | 37.73 | 0.23 |
| 6287 | 74.42 | 37.73 | 0.49 | 5880 | 48.80 | 37.73 | 0.23 |
| 14273 | 73.73 | 37.73 | 0.49 | 7542 | 48.80 | 37.73 | 0.23 |
| 15523 | 73.07 | 37.73 | 0.48 | 8257 | 48.62 | 37.73 | 0.22 |
| 15759 | 72.46 | 37.73 | 0.48 | **9179** | ***45.95** | **37.73** | **0.18** |
| 15940 | 57.87 | 37.73 | 0.35 | | | | |
| 29829 | 51.26 | 37.73 | 0.26 | | | | |

| Before improvements | | | | After improvements | | | |
|---|---|---|---|---|---|---|---|
| Time (secs) | Best integer (stons) | Best node (stons) | Gap | Time (secs) | Best integer (stons) | Best node (stons) | Gap |
| 38162 | 47.33 | 37.73 | 0.20 | | | | |
| 38579 | 46.72 | 37.73 | 0.19 | | | | |
| 38857 | 46.64 | 37.73 | 0.19 | | | | |
| 43718 | 44.00 | 37.73 | 0.14 | | | | |
| **71495** | ***43.96** | **37.73** | **0.14** | | | | |

Table 11. **Results of scenario A (exact method).**

* These figures are the best feasible solutions before the run is interrupted after 100,000 seconds (27 hours and 47 minutes). No further improvement is achieved.

| Before improvements | | | After improvements | | |
|---|---|---|---|---|---|
| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) | Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
| V1 – V4 | 35 | 297.27 | V1 – V4 | 4 | 296.08 |
| V5 – V8 | 78 | 277.27 | V5 – V8 | 14 | 276.08 |
| V9 – V12 | 978 | 210.38 | V9 – V12 | 914 | 206.76 |
| V13 – V16 | 1878 | 147.38 | V13 – V16 | 1814 | 143.76 |
| V17 – V20 | 2778 | 84.38 | V17 – V20 | 2714 | 80.76 |
| V21 – V22 | **2874** | **52.88** | V21 – V22 | **2722** | **49.72** |

Table 12. **Results of scenario A (heuristic with four-vehicle groups).**

| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
|---|---|---|
| V19 - V22 | 900 | 228.40 |
| V15 - V18 | 1800 | 165.40 |
| V11 - V14 | 2700 | 102.40 |
| V7 - V10 | 3600 | 60.90 |
| V3 - V7 | 4500 | 47.80 |
| V1 - V2 | **4501** | **45.43** |

Table 13. **Results of scenario A (heuristic with four-vehicle groups) (vehicles dispatched backwards).**

| Before improvements | | | After improvements | | |
|---|---|---|---|---|---|
| **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** | **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** |
| V1 – V2 | 10 | 303.45 | V1 – V2 | 1 | 302.27 |
| V3 – V4 | 20 | 298.59 | V3 – V4 | 2 | 297.27 |
| V5 – V6 | 33 | 288.59 | V5 – V6 | 4 | 287.27 |
| V7 – V8 | 40 | 278.59 | V7 – V8 | 6 | 277.27 |
| V9 – V10 | 280 | 240.77 | V9 – V10 | 48 | 242.05 |
| V11 – V12 | 427 | 209.27 | V11 – V12 | 55 | 209.92 |
| V13 – V14 | 538 | 177.77 | V13 – V14 | 64 | 178.42 |
| V15 – V16 | 602 | 146.27 | V15 – V16 | 67 | 146.92 |
| V17 – V18 | 728 | 114.77 | V17 – V18 | 72 | 115.42 |
| V19 – V20 | 890 | 83.27 | V19 – V20 | 77 | 83.92 |
| V21 – V22 | **1055** | **53.31** | V21 – V22 | **81** | **52.42** |

Table 14. **Results of scenario A (heuristic with two-vehicle groups).**

| **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** |
|---|---|---|
| V21 – V22 | 6 | 264.64 |
| V19 – V20 | 11 | 231.07 |
| V17 – V18 | 33 | 199.57 |
| V15 – V16 | 47 | 168.07 |
| V13 – V14 | 69 | 136.57 |
| V11 – V12 | 80 | 105.07 |
| V9 – V10 | 86 | 73.57 |
| V7 – V8 | 87 | 63.57 |
| V5 – V6 | 89 | 53.57 |
| V3 – V4 | 112 | 48.62 |
| V1 – V2 | **113** | **46.25** |

Table 15. **Results of scenario A (heuristic with two-vehicle groups) (vehicles dispatched backwards).**

| Before improvements | | | After improvements | | |
|---|---|---|---|---|---|
| Time (secs) | Best integer (stons) | Best node (stons) | Time (secs) | Best integer (stons) | Best node (stons) |
| 0 | 152.42 | 0.00 | 0 | 152.42 | 0.00 |
| 1530 | 89.84 | 0.00 | 232 | 54.98 | 0.00 |
| 1657 | 64.69 | 0.00 | 296 | 31.98 | 0.00 |
| 1911 | 63.92 | 0.00 | 680 | 23.85 | 0.00 |
| 3308 | 54.75 | 0.00 | 701 | 22.11 | 0.00 |
| 3944 | 53.16 | 0.00 | 723 | 12.49 | 0.00 |
| 4071 | 48.51 | 0.00 | 744 | 10.60 | 0.00 |
| 4198 | 46.57 | 0.00 | 787 | 8.62 | 0.00 |
| 4325 | 35.08 | 0.00 | 802 | 8.10 | 0.00 |
| 5214 | 30.90 | 0.00 | 1171 | 4.40 | 0.00 |
| 6865 | 30.73 | 0.00 | 1218 | 0.24 | 0.00 |
| 7246 | 22.59 | 0.00 | 1226 | 0.20 | 0.00 |
| 7284 | 22.47 | 0.00 | **2366** | **0.20** | **0.00** |
| 8644 | 13.93 | 0.00 | | | |
| 9152 | 9.74 | 0.00 | | | |
| 9660 | 8.67 | 0.00 | | | |
| 12455 | 8.30 | 0.00 | | | |
| 12709 | 4.04 | 0.00 | | | |
| 13064 | 3.31 | 0.00 | | | |
| 14233 | 0.32 | 0.00 | | | |
| 17477 | 0.20 | 0.00 | | | |
| 23024 | 0.20 | 0.00 | | | |
| 31802 | 0.12 | 0.00 | | | |
| **37538** | **0.12** | **0.00** | | | |

Table 16. **Results of scenario B (exact method).**

| Before improvement | | | After improvement | | |
|---|---|---|---|---|---|
| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) | Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
| V1 – V4 | 30 | 143.95 | V1 – V4 | 3 | 143.95 |
| V5 – V8 | 930 | 124.59 | V5 – V8 | 903 | 125.41 |
| V9 – V12 | 1830 | 60.55 | V9 – V12 | 1803 | 61.37 |
| V13 – V16 | 2730 | 14.06 | V13 – V16 | 2403 | 14.88 |
| V17 – V20 | 3630 | 1.70 | V17 – V20 | 3303 | 1.91 |

| Before improvement | | | After improvement | | |
|---|---|---|---|---|---|
| **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** | **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** |
| V21 – V22 | **3662** | **0.97** | V21 – V22 | **3306** | **0.77** |

Table 17. **Results of scenario B (heuristic with four-vehicle groups).**

| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
|---|---|---|
| V19 - V22 | 900 | 85.99 |
| V15 - V18 | 1800 | 27.54 |
| V11 - V14 | 2047 | 5.10 |
| V7 - V10 | 2625 | 0.96 |
| V3 - V7 | 3525 | 0.63 |
| V1 - V2 | **3526** | **0.32** |

Table 18. **Results of scenario B (heuristic with four-vehicle groups) (vehicles dispatched backwards).**

| Before improvement | | | After improvement | | |
|---|---|---|---|---|---|
| **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** | **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** |
| V1 – V2 | 11 | 150.14 | V1 – V2 | 1 | 150.14 |
| V3 – V4 | 25 | 143.95 | V3 – V4 | 3 | 143.95 |
| V5 – V6 | 40 | 133.95 | V5 – V6 | 5 | 133.95 |
| V7 – V8 | 66 | 124.56 | V7 – V8 | 8 | 124.56 |
| V9 – V10 | 122 | 92.02 | V9 – V10 | 17 | 92.02 |
| V11 – V12 | 265 | 60.52 | V11 – V12 | 28 | 60.52 |
| V13 – V14 | 408 | 29.02 | V13 – V14 | 35 | 29.02 |
| V15 – V16 | 429 | 14.03 | V15 – V16 | 36 | 14.03 |
| V17 – V18 | 572 | 6.56 | V17 – V18 | 49 | 6.56 |
| V19 – V20 | 644 | 2.33 | V19 – V20 | 56 | 2.33 |
| V21 – V22 | **691** | **1.08** | **V21 – V22** | **59** | **1.08** |

Table 19. **Results of scenario B (heuristic with two-vehicle groups).**

| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
|---|---|---|
| V21 – V22 | 57 | 118.53 |
| V19 – V20 | 61 | 85.99 |
| V17 – V18 | 78 | 54.49 |
| V15 – V16 | 95 | 27.54 |
| V13 – V14 | 97 | 12.55 |
| V11 – V12 | 103 | 5.10 |
| V9 – V10 | 107 | 1.39 |
| V7 – V8 | 117 | 0.96 |
| V5 – V6 | 137 | 0.94 |
| V3 – V4 | 140 | 0.63 |
| V1 – V2 | **141** | **0.32** |

Table 20. **Results of scenario B (heuristic with two-vehicle groups) (vehicles dispatched backwards).**

| Before improvements | | | After improvements | | |
|---|---|---|---|---|---|
| Time (secs) | Best integer (stons) | Best node (stons) | Time (secs) | Best integer (stons) | Best node (stons) |
| 0 | 143.85 | 0.00 | 0 | 143.85 | 0.00 |
| 1213 | 56.45 | 0.00 | 133 | 15.90 | 0.00 |
| 1808 | 49.30 | 0.00 | 315 | 7.00 | 0.00 |
| 2328 | 45.15 | 0.00 | 340 | 3.20 | 0.00 |
| 2477 | 38.75 | 0.00 | 567 | 3.14 | 0.00 |
| 2849 | 34.55 | 0.00 | **962** | **0.00** | **0.00** |
| 3518 | 29.41 | 0.00 | | | |
| 3592 | 28.23 | 0.00 | | | |
| 3667 | 22.18 | 0.00 | | | |
| 3741 | 20.99 | 0.00 | | | |
| 3964 | 11.79 | 0.00 | | | |
| 4931 | 10.00 | 0.00 | | | |
| 7681 | 8.75 | 0.00 | | | |
| 7756 | 4.95 | 0.00 | | | |
| 8648 | 2.40 | 0.00 | | | |
| 9786 | 0.35 | 0.00 | | | |
| **10842** | **0.00** | **0.00** | | | |

Table 21. **Results of scenario C (exact method).**

| Before improvements | | | After improvements | | |
|---|---|---|---|---|---|
| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) | Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
| V1 – V4 | 39 | 135.29 | V1 – V4 | 5 | 135.29 |
| V5 – V8 | 939 | 116.78 | V5 – V8 | 905 | 116.82 |
| V9 – V12 | 1839 | 52.78 | V9 – V12 | 1805 | 52.32 |
| V13 – V16 | 2739 | 13.22 | V13 – V16 | 2705 | 11.97 |
| V17 – V20 | 3639 | 0.06 | V17 – V20 | 2712 | 0.01 |
| V21 – V22 | **3642** | **0.00** | V21 – V22 | **2712** | **0.00** |

Table 22. **Results of scenario C (heuristic with four-vehicle groups).**

| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
|---|---|---|
| V19 - V22 | 900 | 77.45 |
| V15 - V18 | 1800 | 30.70 |
| V11 - V14 | 2417 | 5.60 |
| V7 - V10 | 2420 | 0.00 |
| V3 - V7 | 2421 | 0.00 |
| V1 - V2 | **2421** | **0.00** |

Table 23. **Results of scenario C (heuristic with four-vehicle groups) (vehicles dispatched backwards).**

| Before improvements | | | After improvement | | |
|---|---|---|---|---|---|
| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) | Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
| V1 – V2 | 15 | 141.48 | V1 – V2 | 1 | 141.48 |
| V3 – V4 | 27 | 135.29 | V3 – V4 | 2 | 135.29 |
| V5 – V6 | 46 | 125.84 | V5 – V6 | 5 | 125.84 |
| V7 – V8 | 946 | 118.19 | V7 – V8 | 65 | 116.54 |

| Before improvements | | | After improvement | | |
|---|---|---|---|---|---|
| **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** | **Vehicle group** | **Cumulative time (secs)** | **Total unmet demand (stons)** |
| V9 – V10 | 1046 | 85.69 | V9 – V10 | 82 | 84.04 |
| V11 – V12 | 1215 | 54.19 | V11 – V12 | 110 | 52.54 |
| V13 – V14 | 1346 | 31.19 | V13 – V14 | 121 | 29.14 |
| V15 – V16 | 1459 | 13.84 | V15 – V16 | 126 | 10.14 |
| V17 – V18 | 1499 | 2.41 | V17 – V18 | 129 | 1.21 |
| V19 – V20 | 1505 | 0.00 | V19 – V20 | 129 | 0.00 |
| V21 – V22 | **1506** | **0.00** | V21 – V22 | **129** | **0.00** |

Table 24. **Results of scenario C (heuristic with two-vehicle groups).**

| Vehicle group | Cumulative time (secs) | Total unmet demand (stons) |
|---|---|---|
| V21 – V22 | 38 | 109.75 |
| V19 – V20 | 87 | 77.45 |
| V17 – V18 | 109 | 50.85 |
| V15 – V16 | 143 | 30.70 |
| V13 – V14 | 144 | 13.35 |
| V11 – V12 | 147 | 5.60 |
| V9 – V10 | 148 | 0.00 |
| V7 – V8 | 148 | 0.00 |
| V5 – V6 | 148 | 0.00 |
| V3 – V4 | 149 | 0.00 |
| V1 – V2 | **149** | **0.00** |

Table 25. **Results of scenario C (heuristic with two-vehicle groups) (vehicles dispatched backwards).**

## B. TURKISH ARMY SCENARIO

Three different vehicle grouping sizes have been used in the heuristics. The results are given in Chapter V (Table 6).

# LIST OF REFERENCES


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